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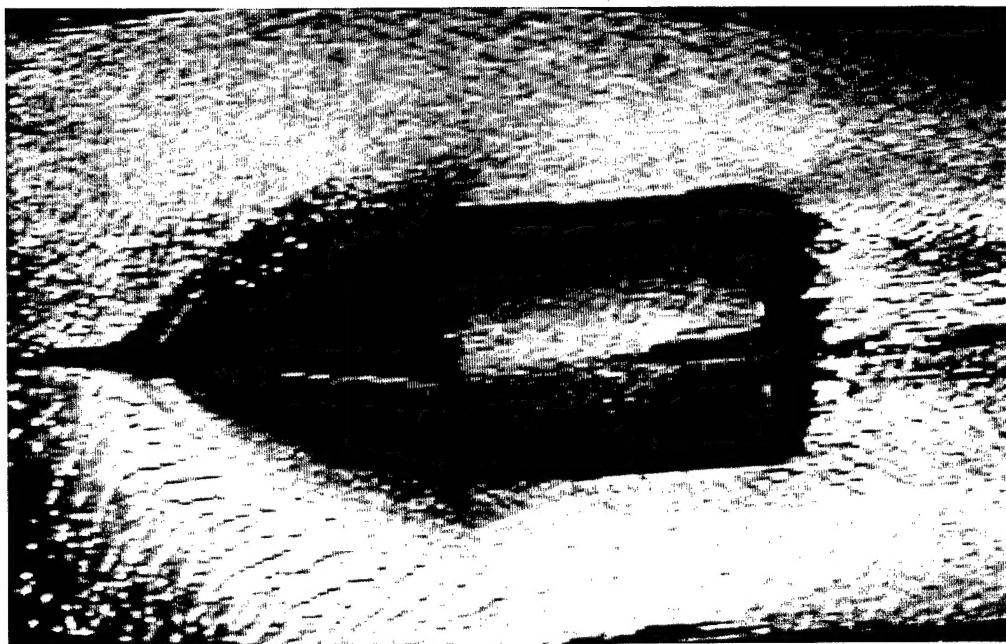
Full Field Surface Shear Stress Measurements using Liquid Crystals

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History

This contract was issued in early 1993 and I made arrangements, through Peter Disimile, to undertake the experimental evaluation of Liquid Crystals in February/March of 1993. At this time Peter spoke with Mr Norman Scaggs at Wright-Patterson AFB and both Peter and I visited the Wright Laboratories. However, due to incorrect procedures I was not allowed access to the Base and had to meet with Norm Scaggs for lunch, where upon I gave him my Passport and Visa numbers for the correct protocol to be set up. It was understood that I would return to the States in September 1993 to undertake the experiments in the Mach 3 wind tunnel facility.

In September I returned, and once again Peter and I visited Norm Scaggs. Unfortunately, I was once again unable to obtain access to the Base and it was Peter who was able to examine the facility and to pass onto me the overall outline of the tunnel configuration. Meanwhile Norm Scaggs was kind enough to provide us with a report and some technical drawings of the facility.

During the winter of 1993 some remedial work had to be performed on this particular facility and in February 1994 I returned, once more, to the States to undertake these

measurements. However, at this time a problem had occurred with some oil infiltration and the tunnel was inoperable and I could not get to see the facility until the day before my departure. Although this was unsatisfactory, I did get to see the tunnel and to arrange ideas for a series of experiments to be performed on my next visit.

The next visit was made in June-July 1994, and this time it was successful. Both Peter and I spent two days at the Base and was able to perform a number of experiments on the high Reynolds number Mach 3 wind tunnel.

It should be noted that although I was unable to perform liquid crystal experiments on the Base, Peter and I did build up some experience of using these crystals on the Mach 2 facility at the Department of Aerospace Engineering at the University of Cincinnati, and some of these are also included in this report.

Introduction

Surface shear stress measurement is of fundamental importance in aerodynamics for studying laminar to turbulent transition, surface vortical structures, drag determination and is a necessary diagnostic requirement for not only large aerodynamic surfaces but also for rotodynamic machinery. Currently, there are many methods for determining the shear stress at the surface ranging from velocity profiles to heated elements and small surface obstacles, but all of them rely upon point measurement of the shear stress value. The advantage of having a methodology to determine the full-field shear stress is, therefore, of immense value to the aerodynamic community. It is this particular area that is to be addressed by reporting the work carried out under the above contract to determine the use of liquid crystals for shear stress measurements at high Mach number.

Without doubt, one of the difficulties with using liquid crystals for shear stress measurements is the calibration of them. Their use at high speed has also not been very successful in the past and this contract was to examine some of the difficulties related to these problems. Therefore, the object of this exercise was two-fold:-

- 1) To determine if liquid crystals would remain attached to the wall in a Mach 3 facility, and
- 2) Could the crystals be responsive to the flow conditions.

The optical properties of thermochromic liquid crystals have been known for many decades, in particular the fact that they will undergo physical changes to their internal structure when acted upon by external stimuli and, in doing so, provide changes in their color component. This color change occurs when incident white light is reflected from the crystal layers.

These liquid crystals may be described as a state between a liquid and solid consisting of planes of molecules forming a helical structure whose characteristic pitch length is within the visible spectrum wavelength range, Figure 1. Their ability to reflect light at select wavelengths is dependent upon their deformation due to certain physical stimuli being applied to them, such as temperature or shear stress. The temperature sensitive crystals are encapsulated and are insensitive to shear, whereas the un-encapsulated crystals are sensitive to shear over a fairly large temperature range, typically 0°C to 60°C, dependent upon their viscosity.

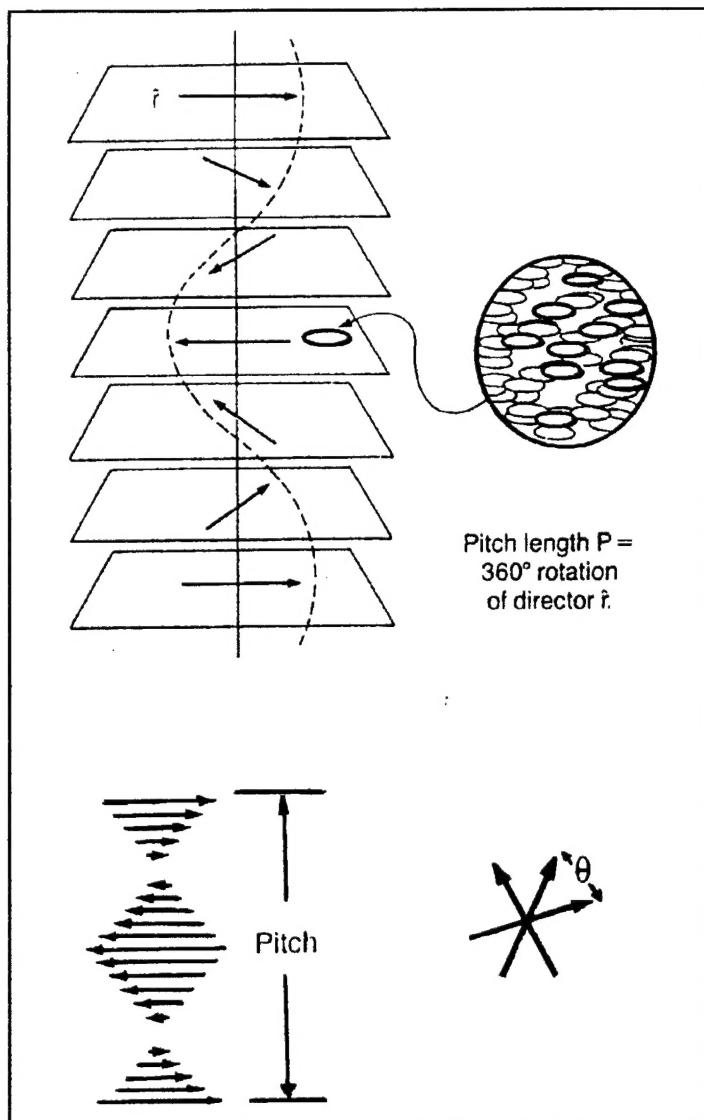


Figure 1 Diagrammatic view of the structure of liquid crystals

For many years liquid crystals have been used for flow visualization of surface flow phenomena in high speed aerodynamic testing. Much of the early work involved the qualitative assessment of parameters such as

- Heat Transfer, Schoeler (1978), Simonich & Moffat (1983)
- Boundary Layer Transition, Klein (1968), Schoeler & Banerji (1983), Holmes et al (1986), Gaudet & Gell (1989), Smith (1990)

- Skin Friction, Gaudet & Gell (1989).

However, not only have these crystals been used for the qualitative aspects of these parameters but some attempts have been made to quantify their color changes. These measurement systems have employed either a color video digitization or photospectroscopy technique and have covered the analysis of

- Temperature Sensitive, Klein (1968), Schoeler (1978), Simonich & Moffat (1983), Schoeler & Banerji (1983), Gaudet & Gell (1989), Akino et al (1989), Toy et al (1991), Farina et al (1993), Roberts & East (1995),
- Shear Stress Sensitive, Klein & Margozzi (1970), Gaudet & Gell (1989), Bonnett et al (1989), Smith (1990), Mee et al (1991), Toy et al (1993), Reda et al (1994), Reda & Muratore (1994).

The problem associated with quantifying shear stress sensitive liquid crystals is inherently more difficult than with the thermochromic ones, for a number of reasons,

- i) the shear stress crystals are unencapsulated and the physical processes occurring within the crystals are not well understood,
- ii) they are prone to contamination, from either the surface or freestream flow,
- iii) for many mixtures the crystals are rapidly eroded from the surface when undergoing high shear stress levels, particularly near leading edges,
- iv) calibration of the color versus shear stress under well-controlled conditions is difficult.

The calibration of these shear stress sensitive crystals has been one of the stumbling blocks of this technique. A number of methods have been attempted such as the use of

a rotational shear rig (Klein & Margozzi 1970, Bonnett et al 1989), measurement of the pressure drop along a pipe (Klein & Margozzi 1969), a time dependent method for the crystals to change from its colorless (focal conic) state to the colorful (grandjean) state in low shear stress areas (Bonnett et al 1989, Mee et al 1991) and the more recent approach of shear stress vector measurement technique on an impinging wall jet using a spectrophotometric analysis (Reda et al 1994, Reda & Muratore 1994). However, few reported successful attempts have been achieved using an aerodynamic calibration.

The method of analysis of the color changes that occur when the crystal is undergoing shear is still a matter for debate, whether to use the frequency, wavelength, a time dependent approach or a color analysis based on the amount of the reflected light. It is this latter technique that this report is based upon.

Method of color analysis

The color analysis is based upon colorimetry in which the primary colors are red, green and blue (RGB), and within an image this RGB space is usually transformed into chromaticity coordinates. This is achieved by reducing the red, green and blue from their absolute values to their proportionate levels:-

$$r = R / (R + G + B)$$

$$g = G / (R + G + B)$$

$$b = B / (R + G + B)$$

However, in this study another coordinate system has been used based upon Hue, Saturation and Intensity (HSI), where hue refers to the color, saturation is a measure of the amount of white light contained in the specific color and intensity is the relative brightness of the color. The relationship between RGB and the HSI spaces may be represented by the RGB triangle shown in the following Figure 2.

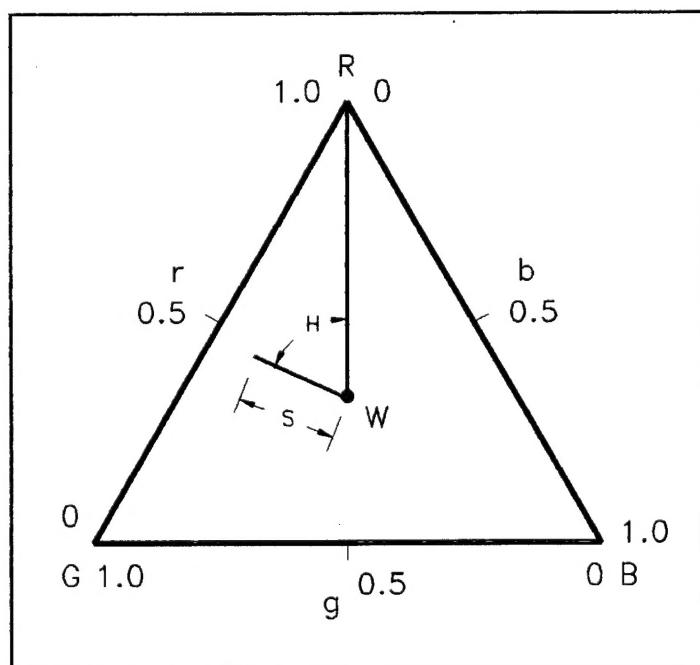


Figure 2. RGB color diagram

Along the sides of the triangle are mixtures of only two of the three primary colors. Hue is defined in terms of the angle between the line joining the 'white point to the color point' and the line joining the 'white point to the red point' at $R = 1$. The saturation of the color is concerned with the distance from the white point to the color point, showing that the colors along a line drawn from the white point has the same hue but increasing saturation. The intensity of the color is a value perpendicular to the color point and represents the brightness. The relationship between HSI and RGB is:-

Intensity $I = (R + G + B) / 3$

Saturation $S = 1 - [\min(R, G, B) / I]$

Hue $H = [90 - \arctan(F / \sqrt{3}) + C] / 360$

where $F = (2R - G - B) / (G - B)$

and $C = 0$ if $G > B$
 $= 180$ if $G < B$

Experimental Arrangement

This experimental program utilized two different high speed tunnel facilities and a video digitizing system for image analysis. A brief overview of these facilities is given below.

Mach 3 Facility

For the purpose of this investigation the Mach 3 high Reynolds number wind tunnel in the Air Force Flight Dynamics Laboratory at Wright Patterson AFB was used. This facility is of the blowdown configuration with a closed working section of 208 mm x 203 mm (8.2" x 8.0"). Operating conditions allow for stagnation pressures of between 50 to 600 psia to be attained with stagnation temperatures of just below ambient being achievable. With these stagnation conditions free-stream unit Reynolds numbers of 2.84×10^5 to 3.66×10^6 per meter (0.93×10^6 to 1.2×10^7 per foot) may be produced. Although nominal run times of the order of 10 minutes could be attained run times of about 120 seconds was used throughout this series of experiments. Furthermore, the tests were conducted at three different stagnation pressures of 100, 300 and 500 psia. The following Figure 3 typically shows how the tunnel parameters varied over the course of any one experiment, with

- a) the upper left diagram indicating the smooth running of the test,
- b) upper right showing when the different stagnation pressures were available,
- c) lower left the stagnation temperature throughout the run in degree Rankine, and
- d) the lower right, the wall pressure.

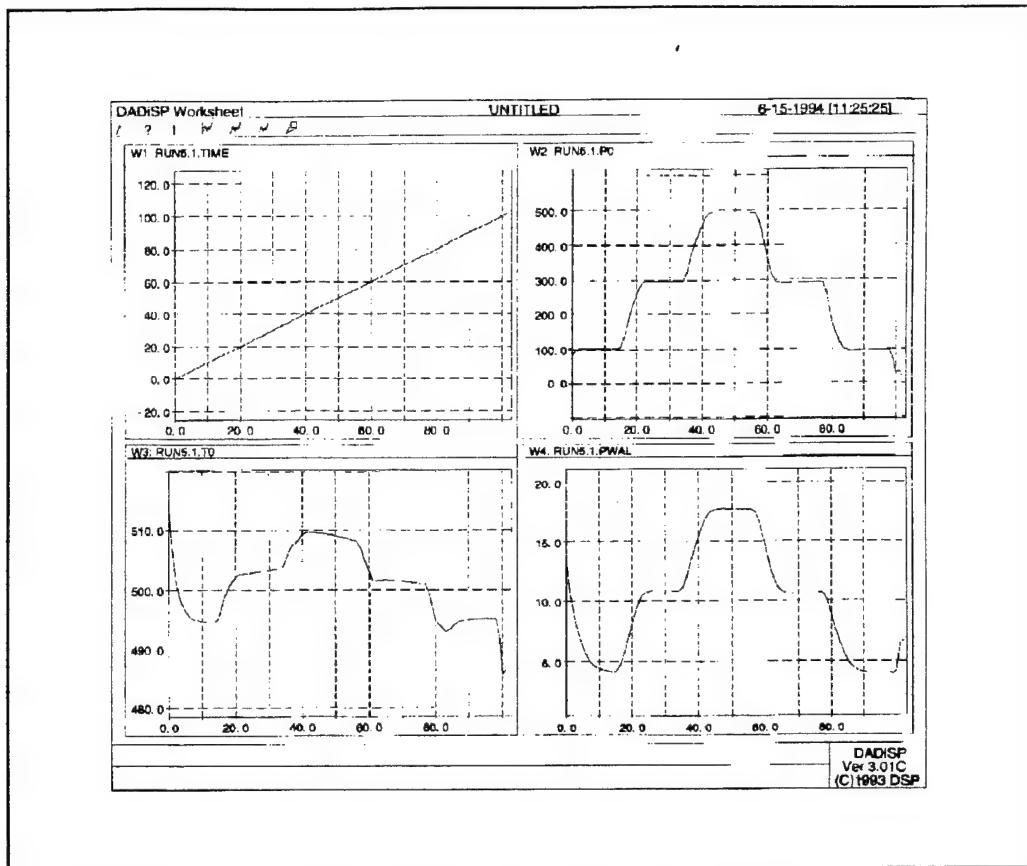


Figure 3. Typical parameters in the Mach 3 facility

The liquid crystals under going test were applied to a 63.5 mm (2.5") diameter aluminum 'plug' that was black anodized and mounted in the top wall of the tunnel at a location close to where shear stress levels had been measured in an earlier program, Fiore (1977). In Fiore's experimental program the local shear stress was measured directly by a floating-element balance manufactured by Kistler Instrumentation Co, as well as indirectly by a Preston tube and by using the Von Karman integral method. The balance was of a sealed unit type having a flat surface allowing flush fitting with the tunnel wall and had a floating element of 0.370" diameter.

Fiore not only measured the local skin friction in this facility but also analyzed other workers data and plotted the results as shown in Figure 4. Although there is some degree of scatter between the different experimental and numerical schemes, the data is in reasonable agreement.

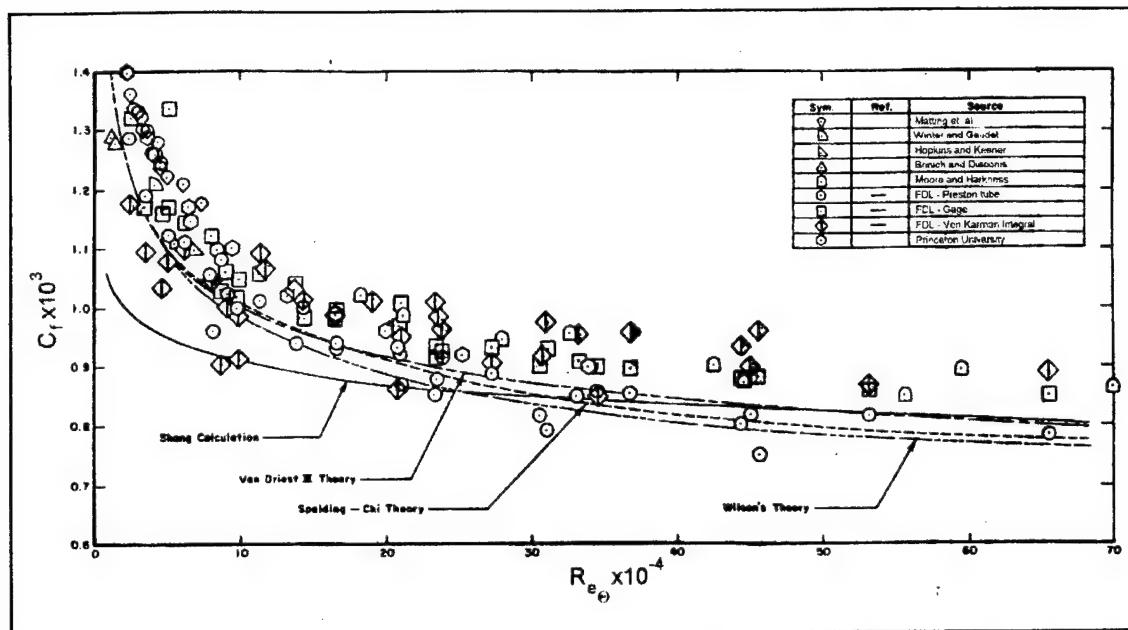


Figure 4. Local Skin Friction Coefficient versus Momentum Reynolds Number at $M_\infty = 2.98$ for Near Adiabatic Wall Conditions - From Fiore (1977)

In order to examine more closely the work performed within this Mach 3 facility, the results from the three methods described above have been replotted in Figure 5. In this figure the data from the Preston tube, skin friction gage and the Von Karman Integral have been curve fitted to show the variation in the three methods, and it can be seen that the degree of scatter of the data about the curve fit for the first two method is very good, whereas there is far more for the VK integral method. For the purpose of this project the data from the skin friction gage was used.

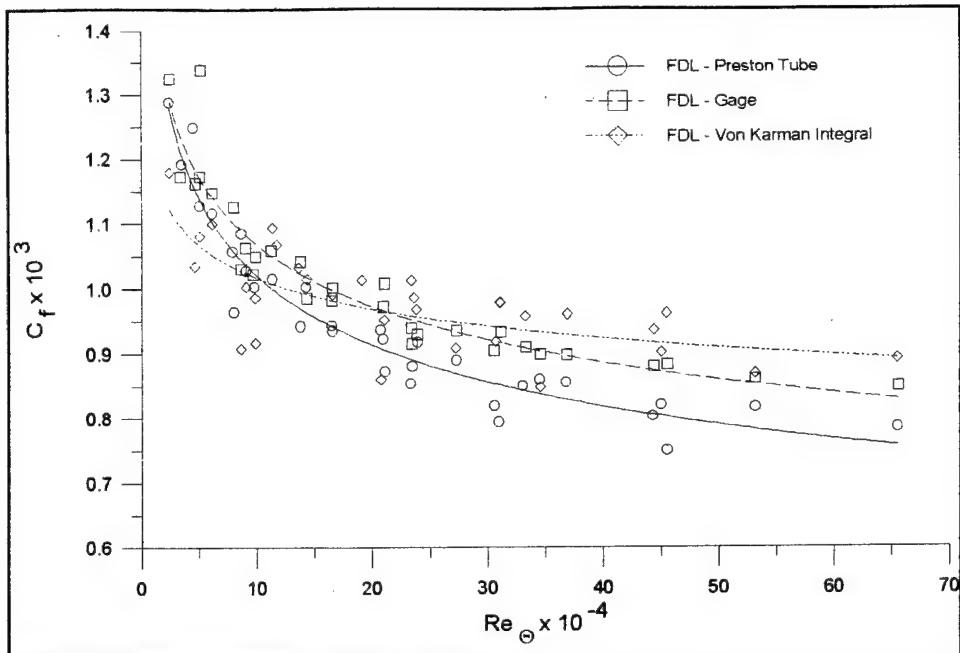


Figure 5. Replotted values of the skin friction versus Re_θ for the Mach 3 tunnel in FDL

The liquid crystal experiments were performed at a location of 838 mm ($x = 33$ in) from the throat and not at one of the convenient stations that Fiore used. Figure 6 shows in diagrammatic form the relative positions of the 'plug', lighting and the camera to the tunnel cross-section.

The liquid crystals were illuminated with a 300W Halogen lamp from a side window in the wall of the tunnel upstream of the 'plug', and they were viewed with a SVHS video camera through a small rectangular window in the floor of the tunnel via a front coated silver mirror set at an angle of 45° .

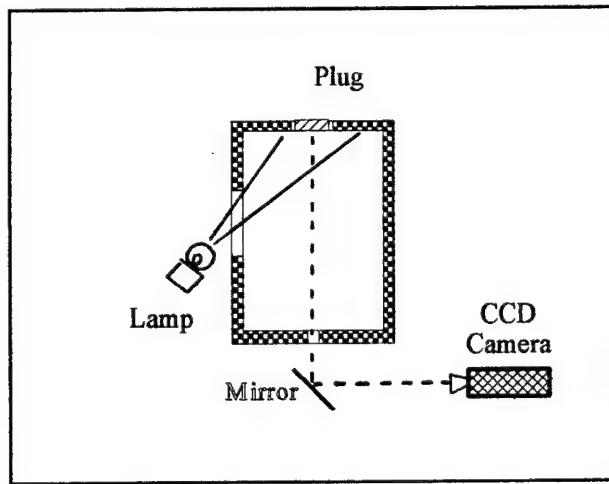


Figure 6. Sketch of the positions of the 'plug', lighting and camera

The following 3 figures show the setup of the camera in relation to the working section of the tunnel. Figure 7 shows the tunnel with the working section door open and the camera mounted looking at the silver coated mirror, Figure 8, and viewing the crystal coated 'plug' through the small rectangular window in the floor of the tunnel, Figure 9.

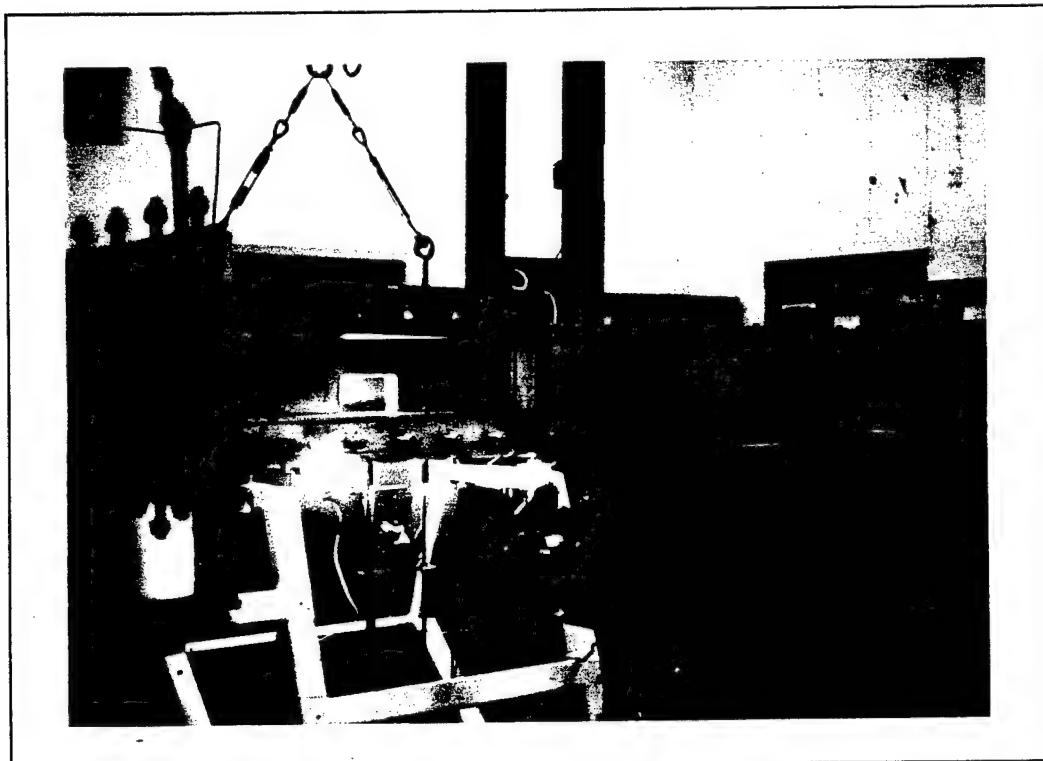


Figure 7. View of the working section of FDL Mach 3 Wind Tunnel with the Camera, mirror and light source

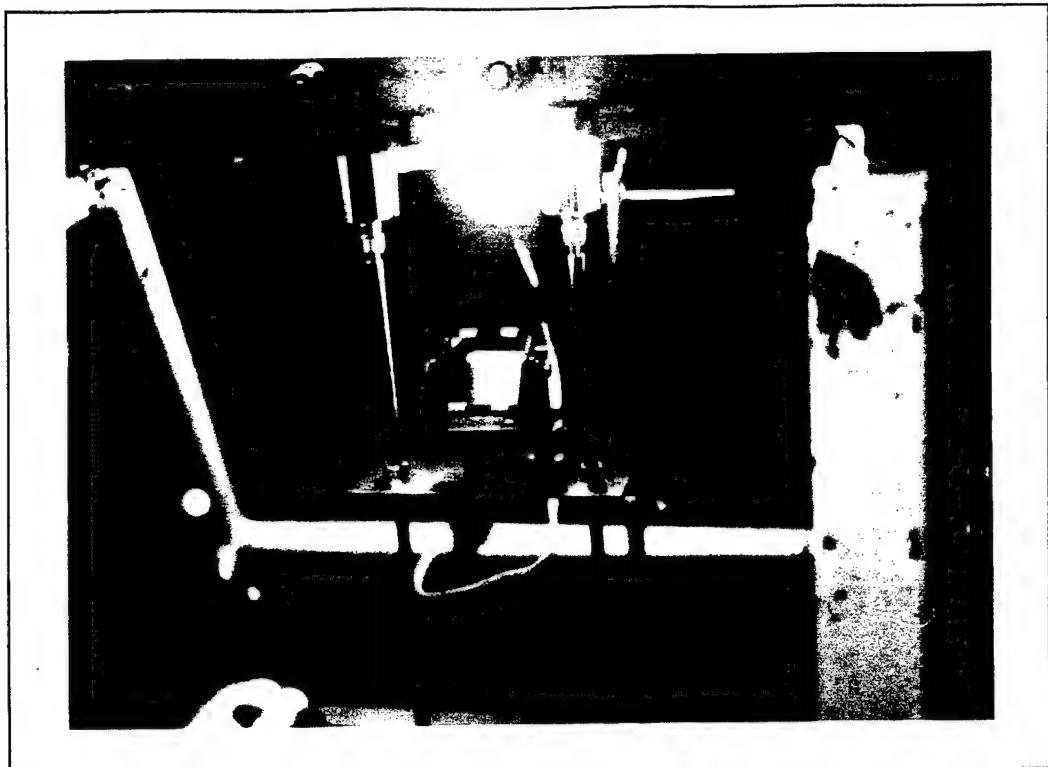


Figure 8. Mirror assembly set at 45°

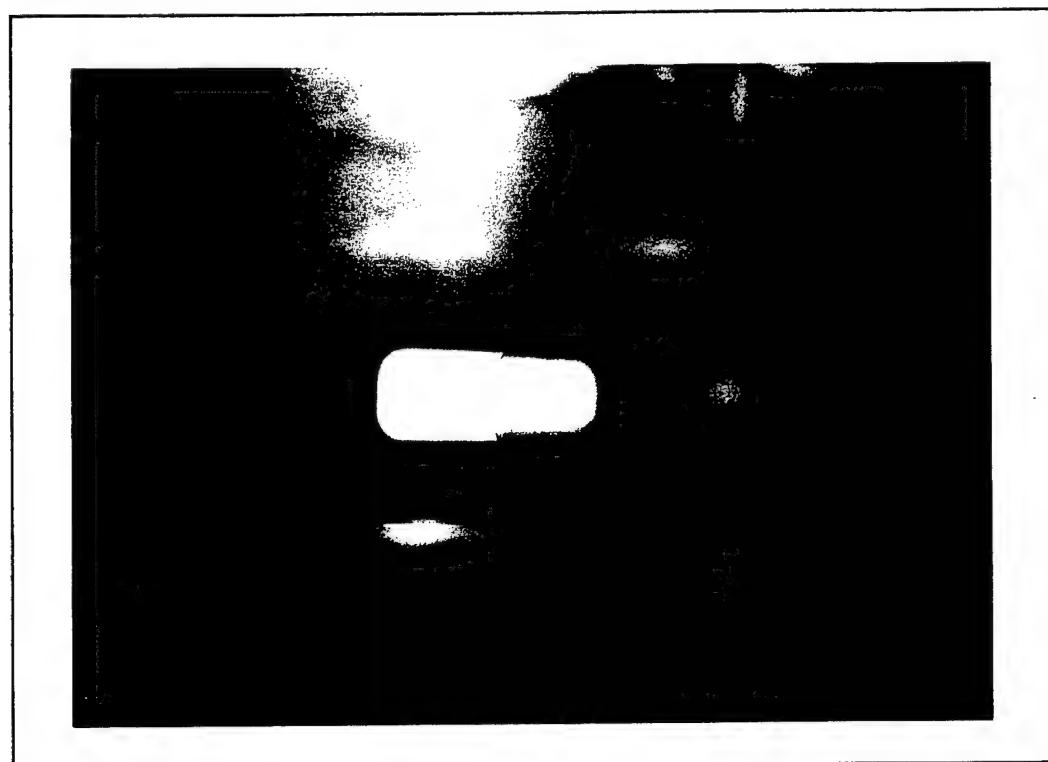


Figure 9. View of the 'plug' seen through the floor window

Video system

The video system employed in this investigation was a Panasonic 3-CCD Color Video Camera WV-F250B and was used with a 1.5" electronic viewfinder WV-VF39. This system was connected to a Panasonic SVHS video cassette recorder AG-7750 for recording the color changes during the experiment for subsequent video digitizing and analysis.

Digitizing system - PC based

The analysis of the color component was performed on each of the desired video frames. This was achieved by digitizing the complete frame, from either the camera or from the SVHS system, using a single Imaging Technology Color Frame Grabber installed in a 486 PC operating at 33 MHz, shown diagrammatically in Figure 10. The images were analyzed using the HSI system outlined above.

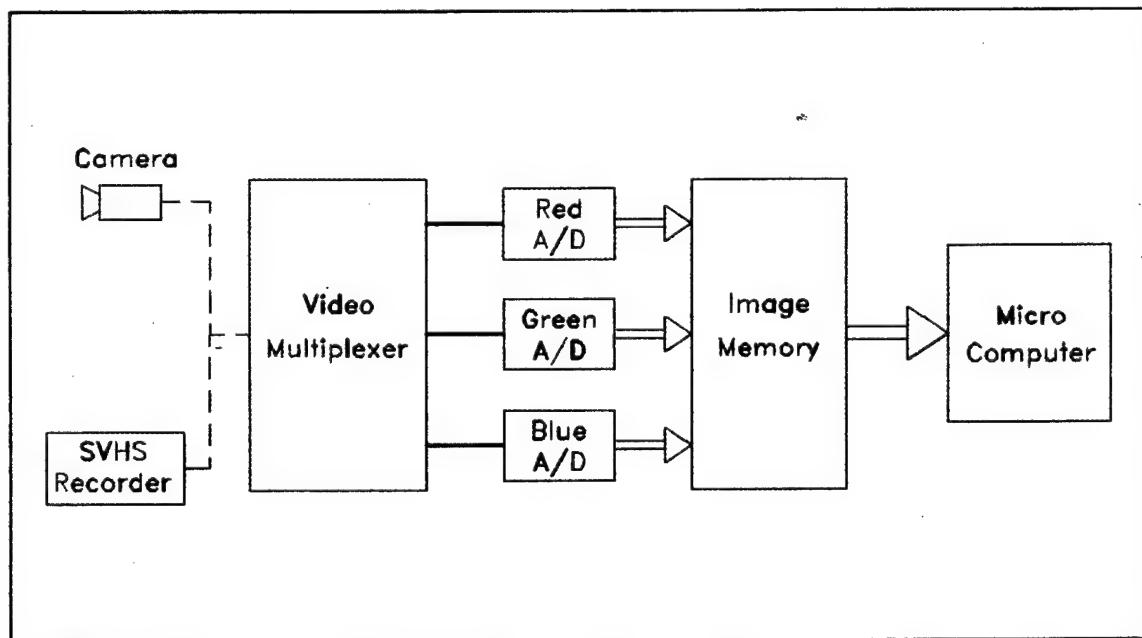


Figure 10. Diagrammatic outline of the video digitizing system

Liquid crystals evaluated

A number of different crystals were used within this project although not necessarily in a particular facility. For example the table below shows a selection of crystals that were evaluated at different times throughout this period although only four of them were tested in the Mach 3 facility and this will be outlined later in the report.

Crystal Mixture	Type	Viscosity (cps)
TI511	chiral-nematic	250
BNR/50C	chiral-nematic	250
BCN/165	mixed	1,000
CN/R2	cholesteric	4,500
CN/R30	cholesteric	7,000
CN/R7	cholesteric	13,000
CN/R8	cholesteric	40,000

Cholesteric are naturally occurring sterols

Chiral-nematic are non-sterol synthetic cholesterics

As shown in the above table the value of the viscosity of the liquid crystal used in this experimental program ranged from 250 to 40,000 cps. However, as will be shown later this parameter is not necessarily one that will provide assistance in determining which crystal

to use for a particular application, a high viscosity does not mean that it will be the most useful at high Mach number or skin friction.

Mach 2 Facility

Throughout the period of this contract further work on the crystals was performed at the University of Cincinnati in their intermittent blow-down facility. This wind tunnel has a working section of 152 mm by 165 mm by 400 mm length (6.0" x 6.5" x 15.75"). An asymmetric sliding contoured nozzle block arrangement may be utilized to vary the freestream Mach number between 1.4 and 3.8. The tunnel is supplied with compressed air, stored in tanks of 60.9 m³ (2150 ft³) at a working pressure of 13.8 MPa (2000 psia), and will provide run times of the order of 4 minutes at Mach 2 and above, allowing Reynolds numbers between 2.6×10^6 /m and 13.1×10^6 /m (8.5×10^6 /ft to 43.0×10^6 /ft) to be achieved. Figure 11 shows a diagrammatic layout of this supersonic wind tunnel while Figure 12 shows a picture of the working section complete with video camera and lights.

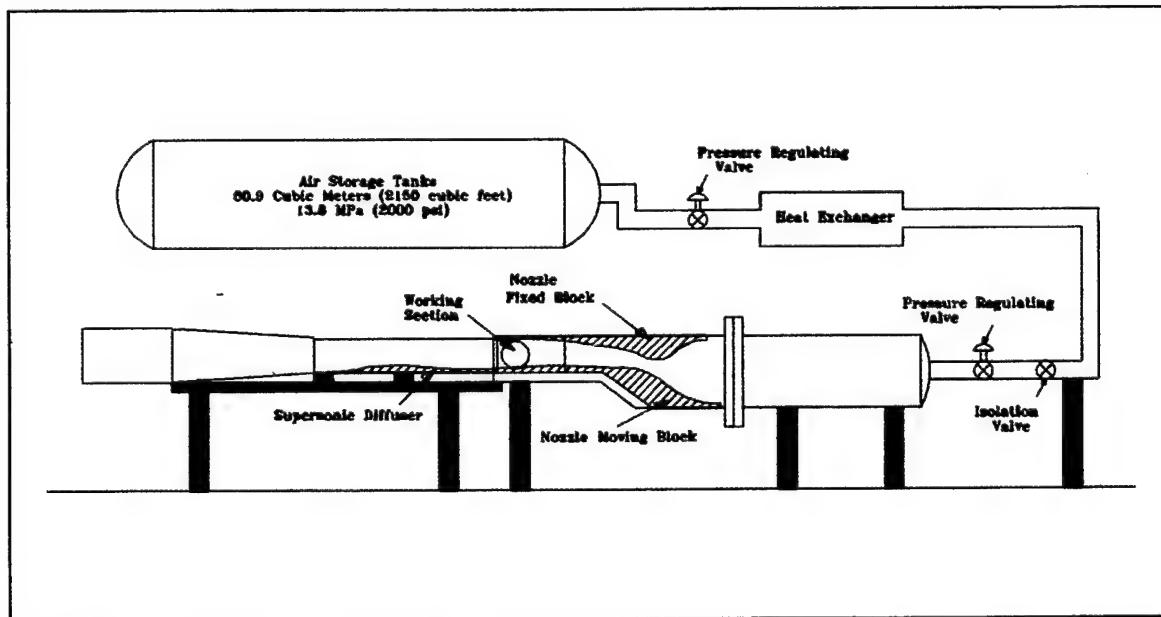


Figure 11. Diagrammatic layout of the Mach 2 facility

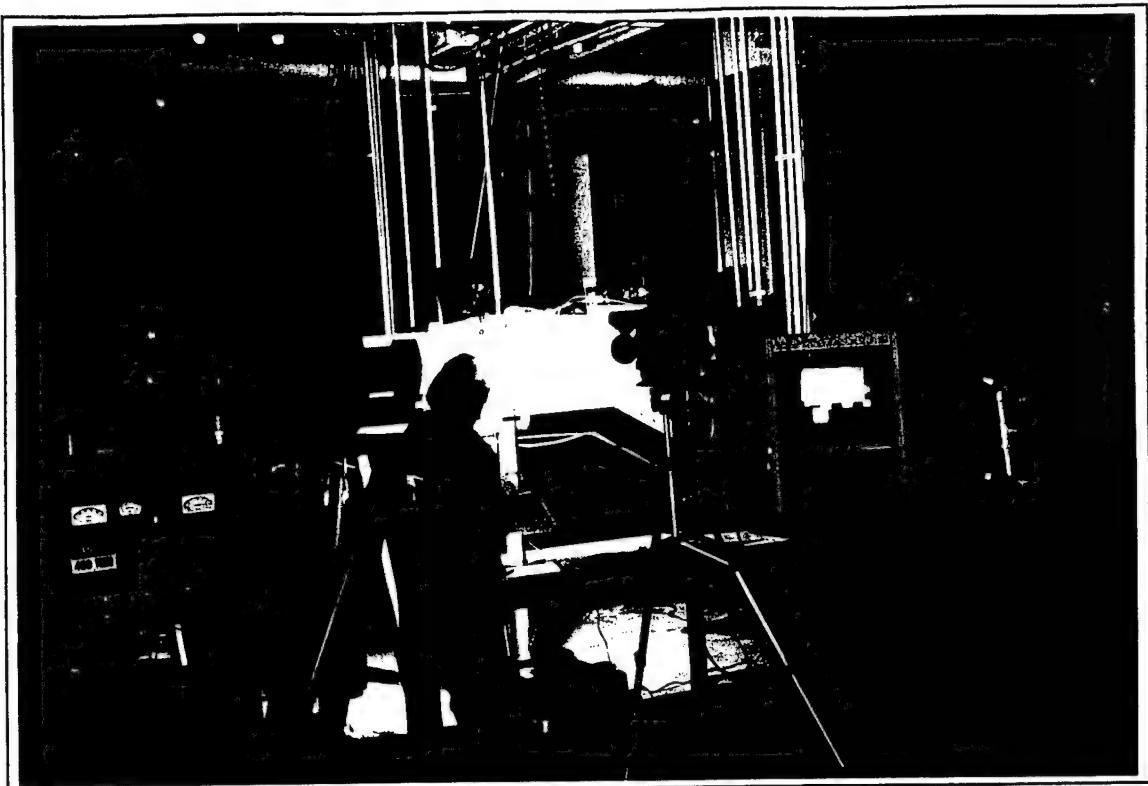


Figure 12. View of the working section of the Mach 2 facility

Results

Since the experimental program covered two high speed facilities the results are discussed in the following two sections.

Results of the Mach 3 Tests

For this particular project four crystal types were chosen to represent the range of different viscosities, these were BCN/165 a mixture of cholesteric/chiral-nematic crystals with a viscosity of 1000 cps, and three cholesteric crystals CN/R2, CN/R7 and CN/R30 having viscosities of 4500, 13000 and 7000 cps respectively. The surface of the black anodized aluminum plug was prepared for each run by cleaning its surface with isopropyl alcohol and allowing time for it to evaporate. Each crystal was then applied to this surface in a thin layer using a fine artists brush. The tunnel was run for approximately 15 seconds at each of the five stagnation pressure settings and the resulting color changes videoed with the CCD camera and stored on a SVHS tape for subsequent analysis. Analysis of the color condition only occurred when the tunnel was at steady state as depicted by the stagnation pressure diagram, as shown in Figure 3 above.

It should be noted that there was some evidence of non uniformity of the color state across the plug on which the crystals were applied. Although it is realistic to assume that the shear stress at the plug location was constant the application of the crystals at the leading edge of the plug area would have provided a small step change, of the order of $50\mu\text{m}$, in the wall boundary giving rise to some variation across the plug surface. This is evident from observing the crystals while the tunnel was starting-up, in which the crystals provided a complete change from red to blue color, Figure 13, indicating a change in hue of 0.2 for red (low shear stress) to 0.6 for blue (high shear stress). This is as expected since during start-up the shear stress would be increasing to its steady state condition.

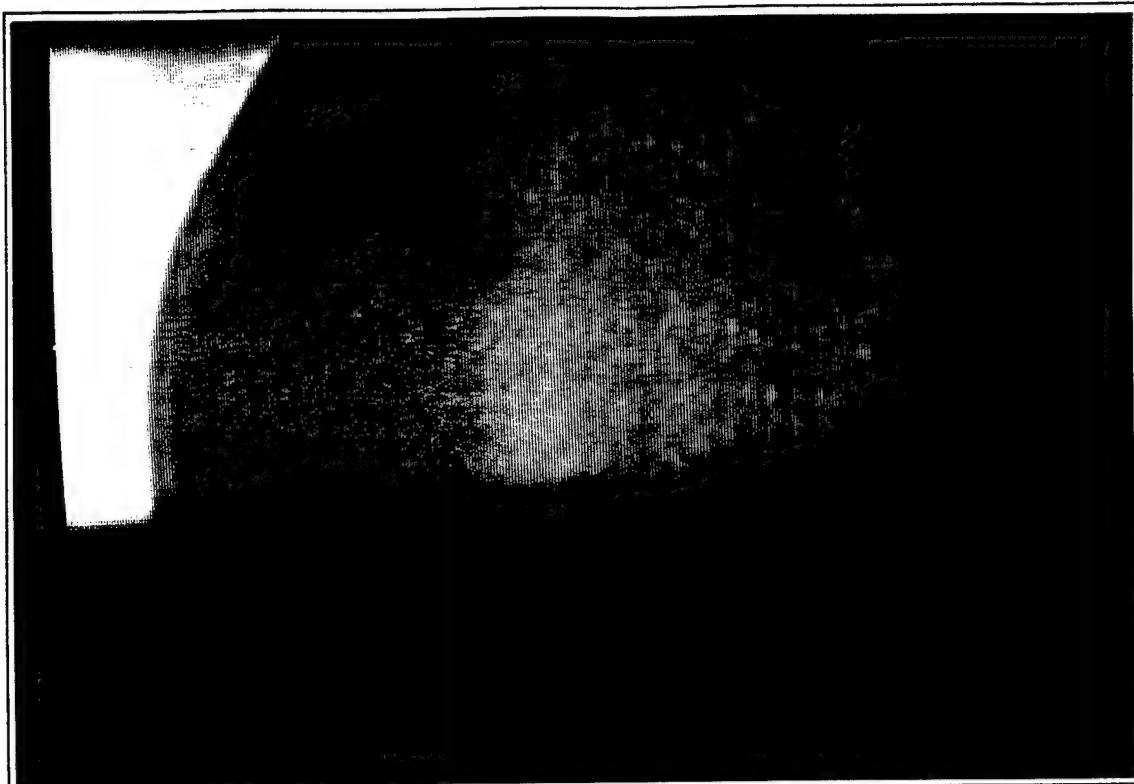


Figure 13. Change in crystal color as the tunnel is starting up

Once the tunnel was at steady state the skin friction was higher than expected and outside the range for two of these crystals and close to the upper limit for the other two. In fact it was the higher viscosity crystals CN/R7 and CN/R30 that were both saturated over the complete shear stress range with CN/R7, in particular, not responding well when the tunnel was shut down. This crystal may have been affected by the temperature changes within the run-time of the experiment in which the tunnel wall temperature dropped below ambient conditions. Although it had changed from the red to the blue state during the run its recovery from the blue color state to the red when the shear stress was removed was very

prolonged, indicating that its response time was severely affected. Although crystal CN/R30 did not suffer the same fate as CN/R7 and returned to the red color state on shutdown, it was saturated over the shear stress range and provided little in terms of calibration. This crystal would be more useful at lower shear stress values.

The other two crystals CNR/165 and CN/R2 both provided a limited calibration over the shear stress range of 150 - 600 Nm² corresponding to hue values between 0.48 and 0.56 respectively (representing a pale shade of blue to a darker shade). Figures 14, 15 and 16 show the changes in color of CNR/165 whereas Figures 17, 18 and 19 show the changes in CN/R2. Although their relative viscosities were different by a factor of four, they both responded well to the applied shear and followed one another closely. Figures 20, 21 and 22 shows how CN/R7 responded badly to the changes in the tunnel conditions by not changing in color.

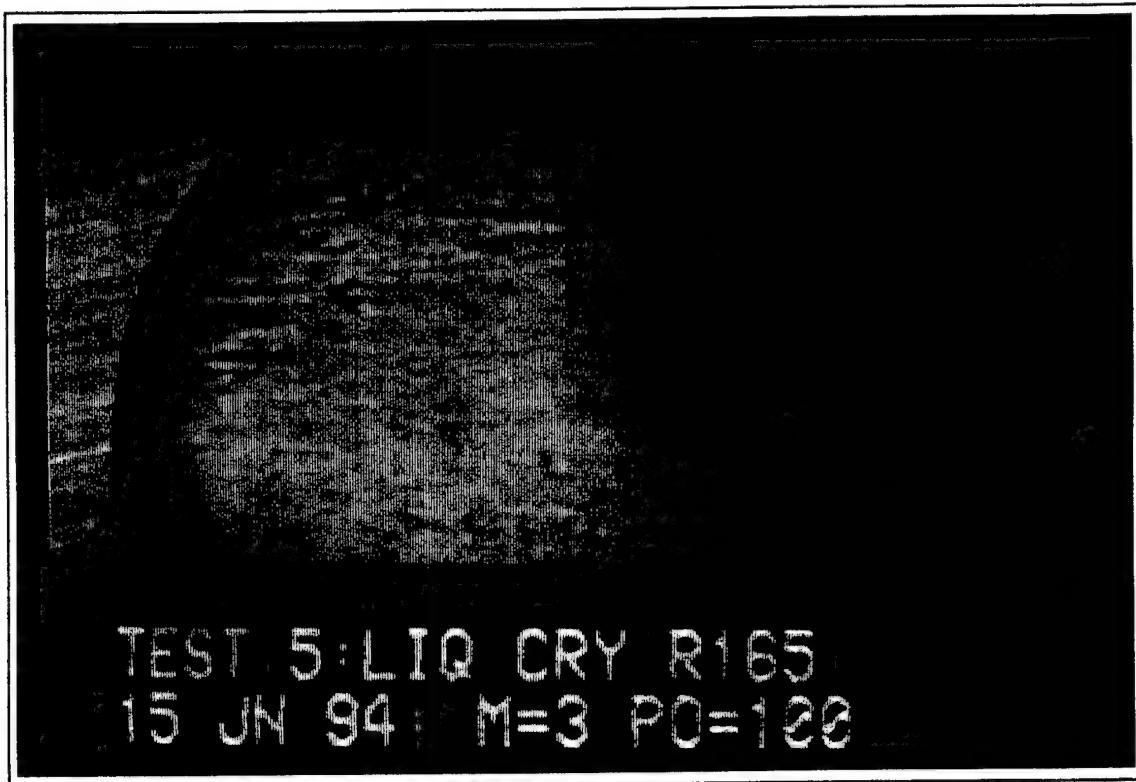


Figure 14. Crystal CNR/165 at stagnation pressure of 100 psia at Mach 3

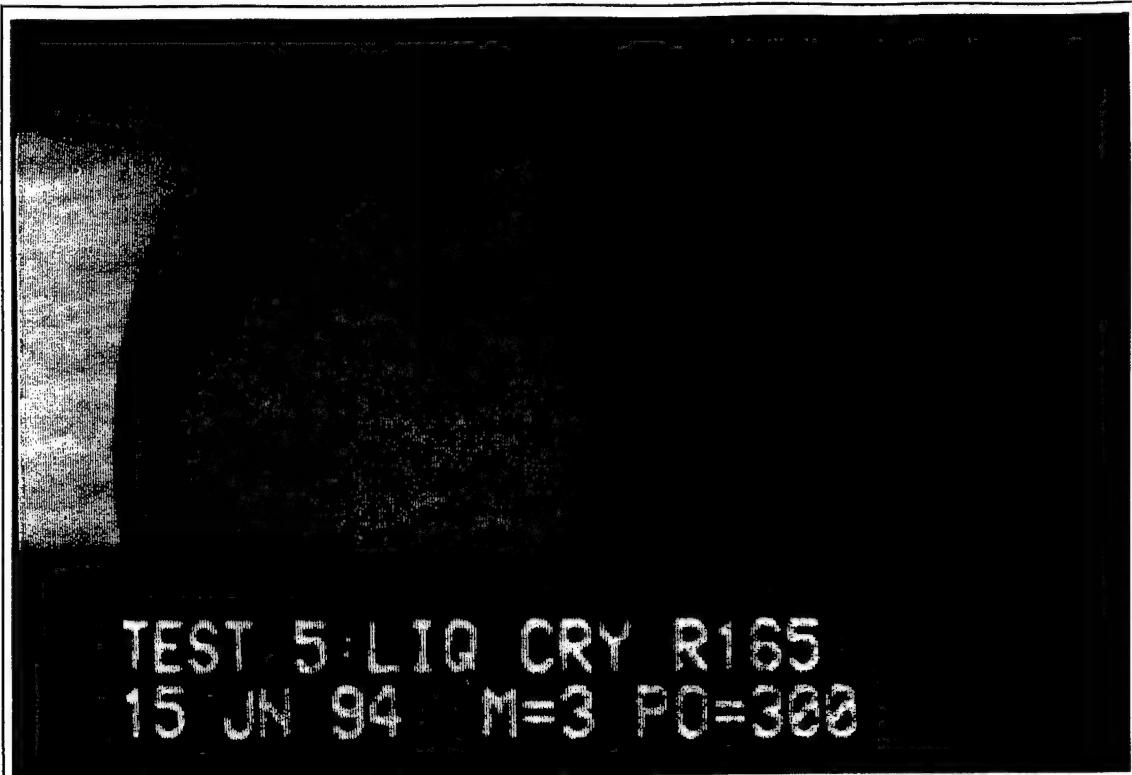


Figure 15. Crystal CNR/165 at stagnation pressure of 300 psia at Mach 3

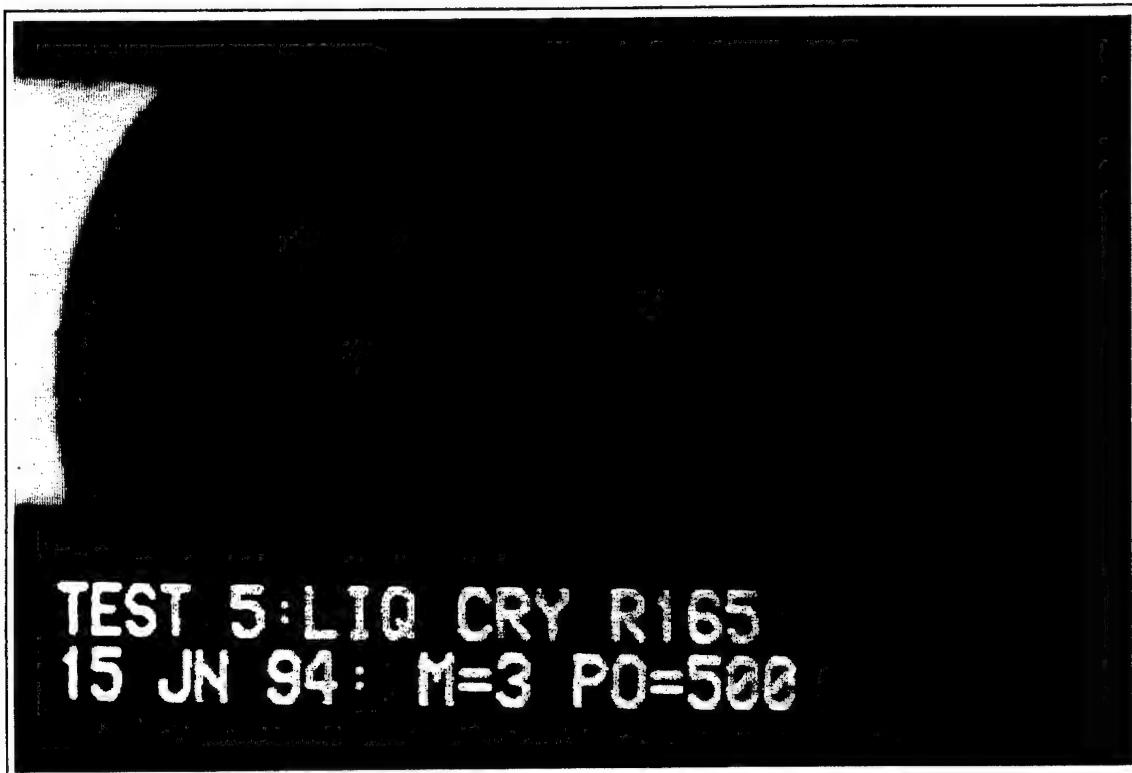


Figure 16. Crystal CNR/165 at stagnation pressure of 500 psia at Mach 3

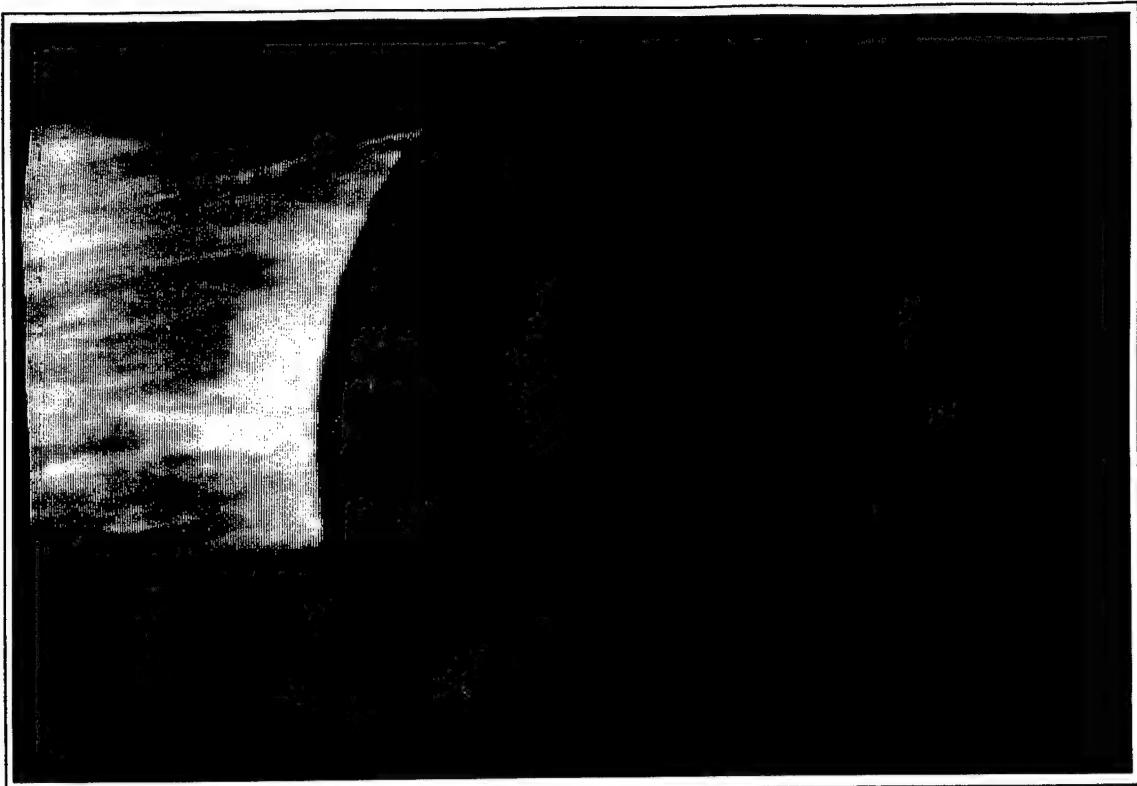


Figure 17. Crystal CN/R2 at stagnation pressure of 100 psia at Mach 3

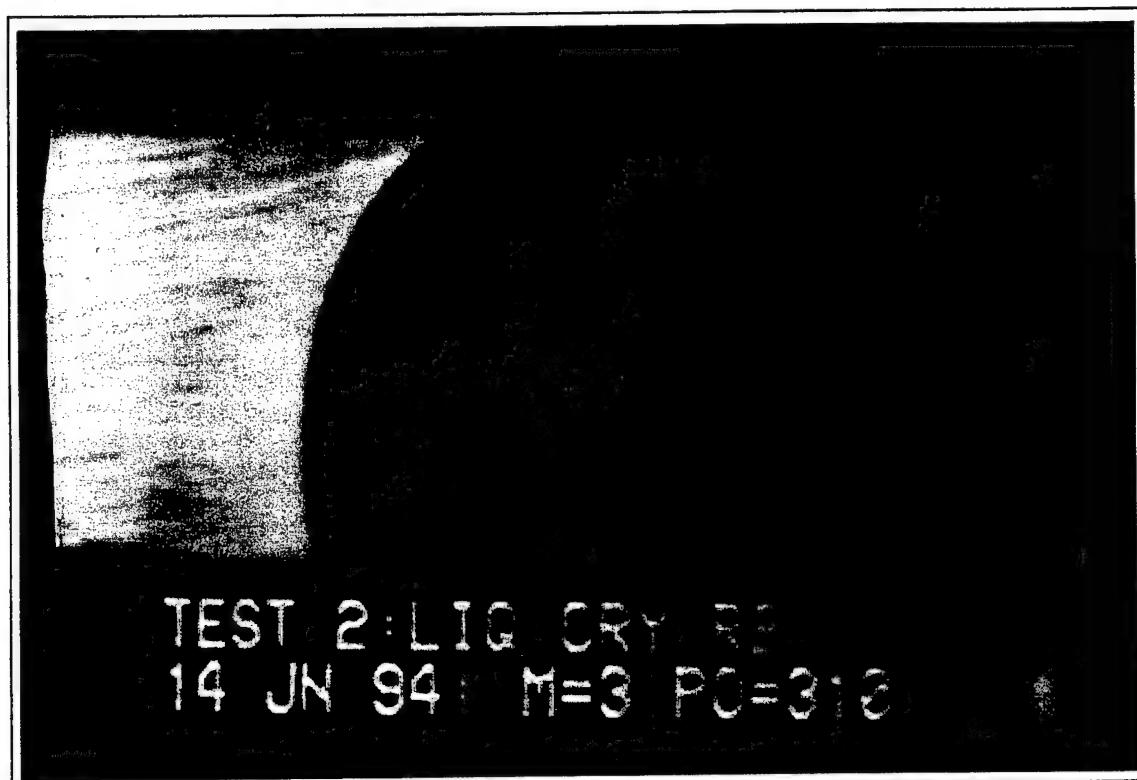


Figure 18. Crystal CN/R2 at stagnation pressure of 310 psia at Mach 3

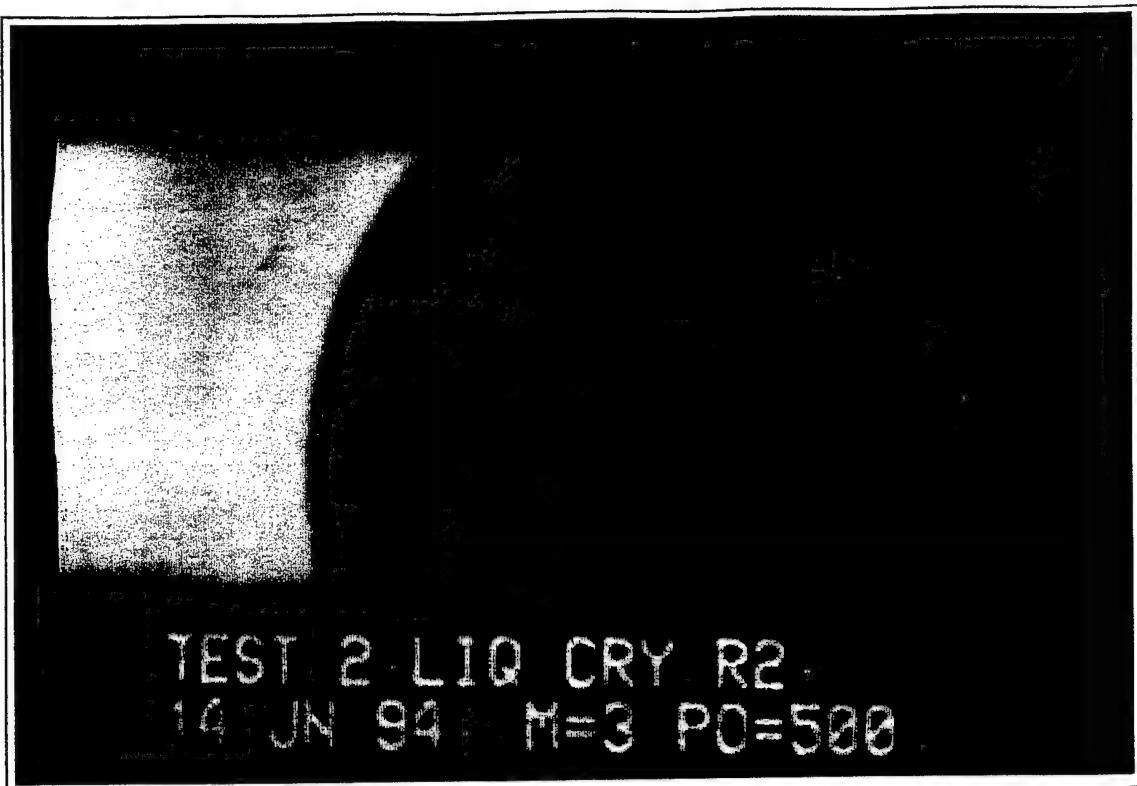


Figure 19. Crystal CN/R2 at stagnation pressure of 500 psia at Mach 3

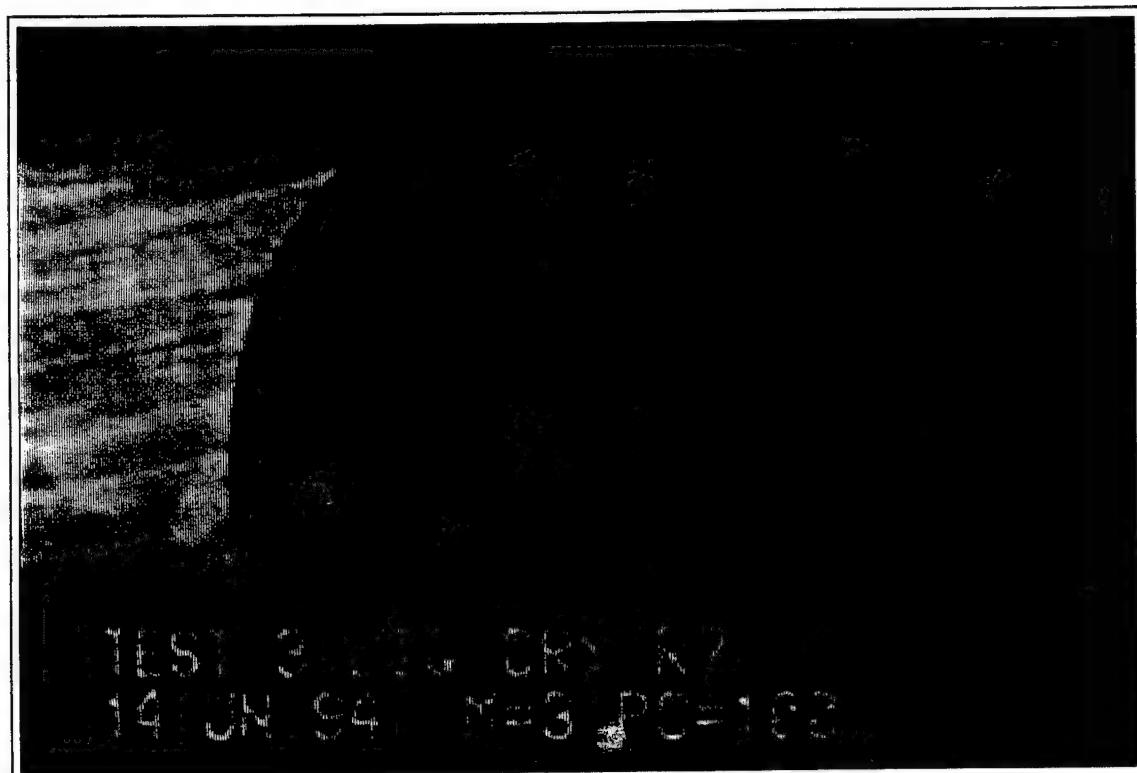


Figure 20. Crystal CN/R7 at stagnation pressure of 100 psia at Mach 3

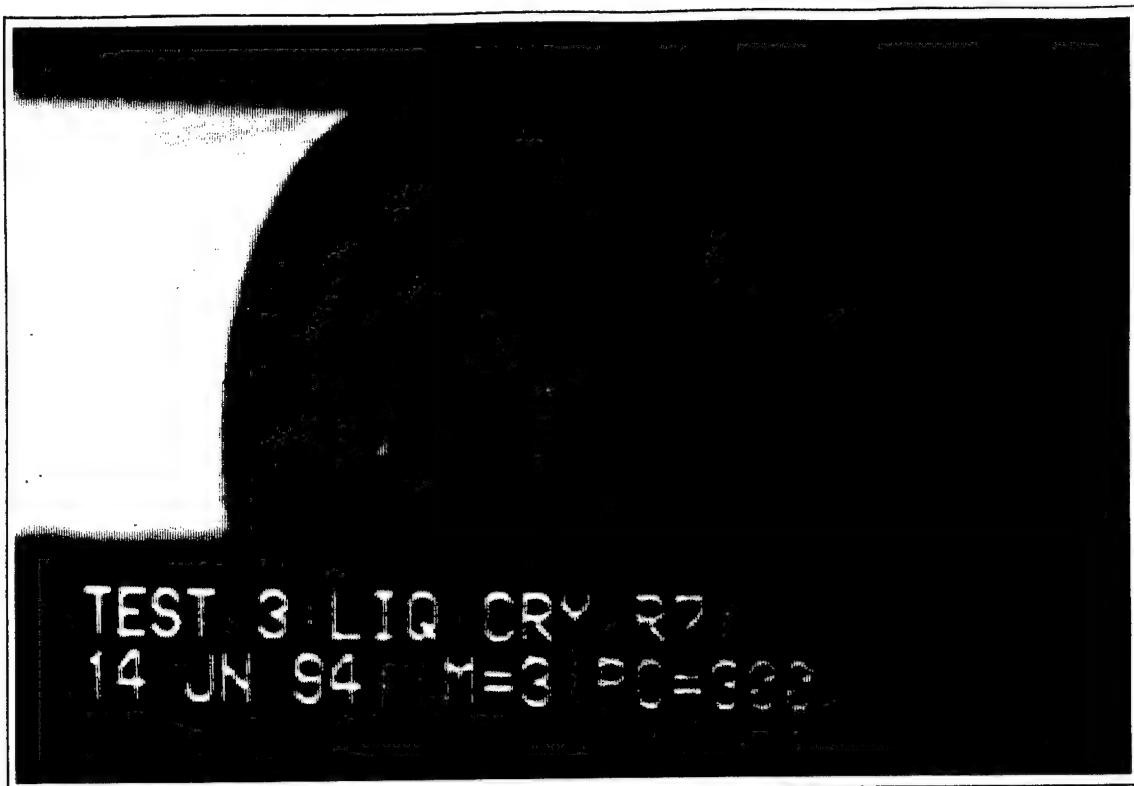


Figure 21. Crystal CN/R7 at stagnation pressure of 300 psia at Mach 3

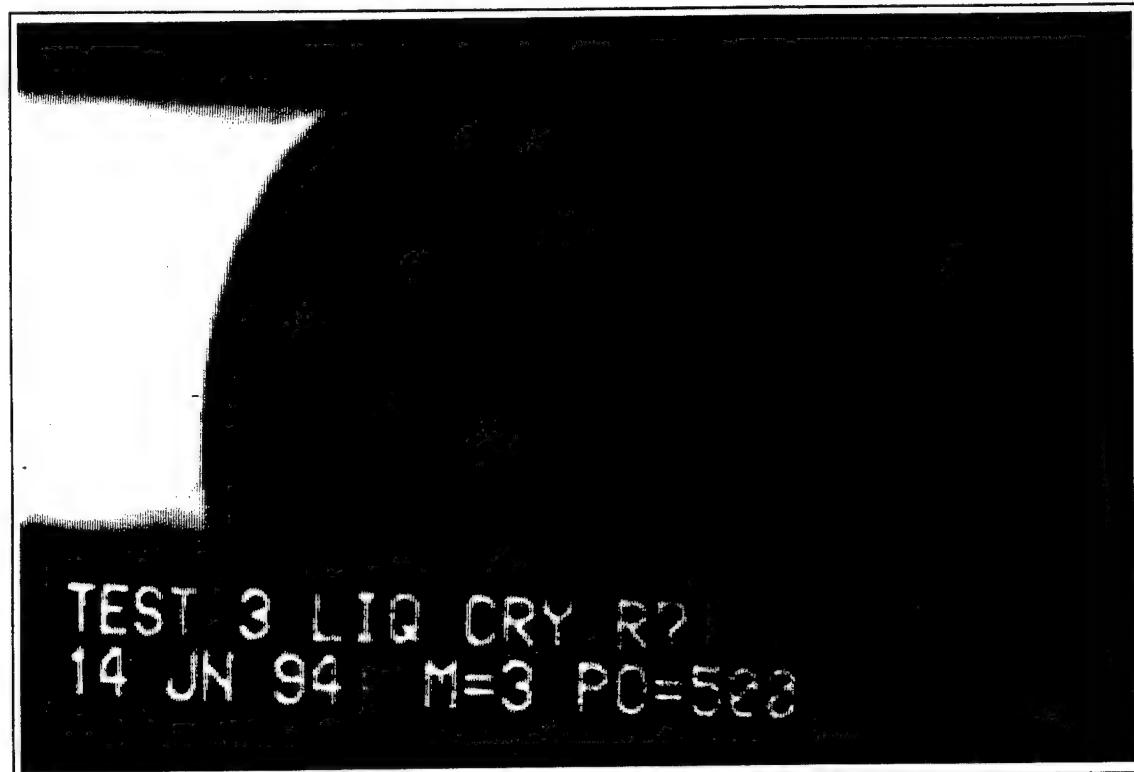


Figure 22. Crystal CN/R7 at stagnation pressure of 500 psia at Mach 3

Both crystals appeared not to be adversely affected by the tunnel wall temperature and returned to the red color state immediately on shut-down of the tunnel, Figure 23.

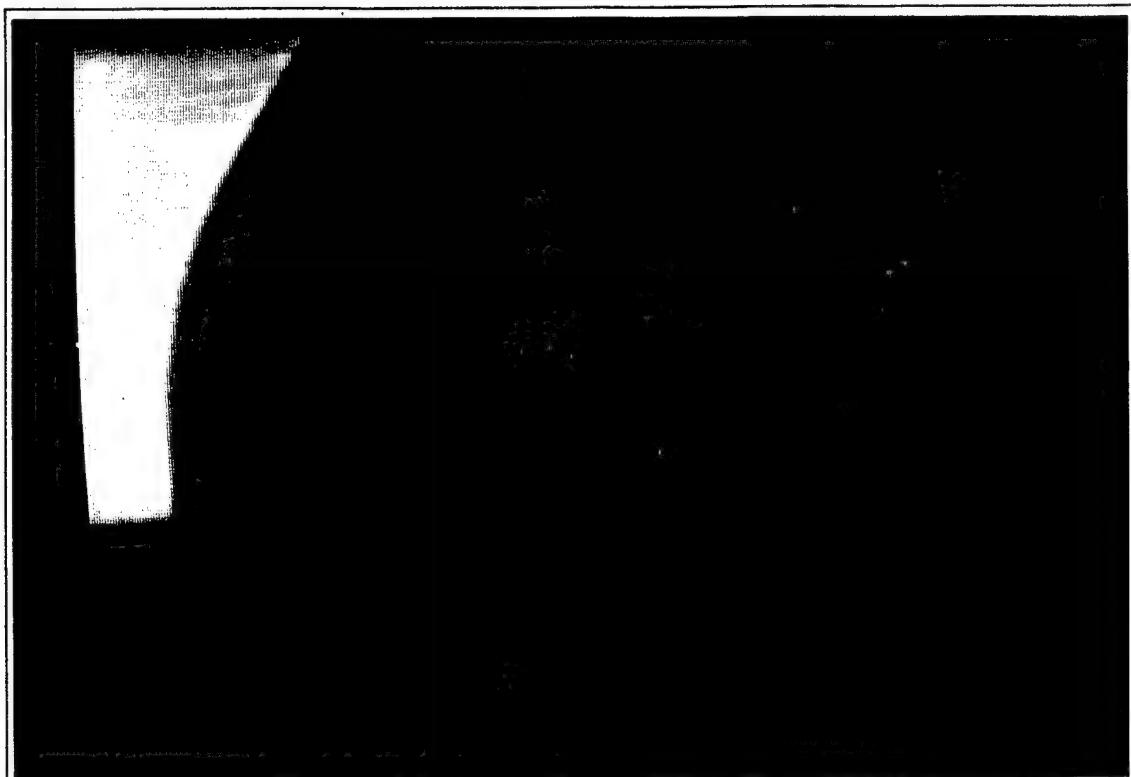


Figure 23. Crystal CNR/165 returns to its original state on shut down of the tunnel

Since it was not possible to view the entire area of the plug, a small 'window' within the visible area was used for calibration analysis, and the hue value averaged over this area. However, even over this small area of interest the value of the hue was not constant. As shown in figures 24, 25 and 26, for CNR/165 the variation of hue for each of the stagnation pressure was of the order of 5%. For the purposes of this work the hue was averaged for each of the different stagnation pressures and this was used to calibrate against the value for the shear stress as determined from the work of Fiore, Figure 5.

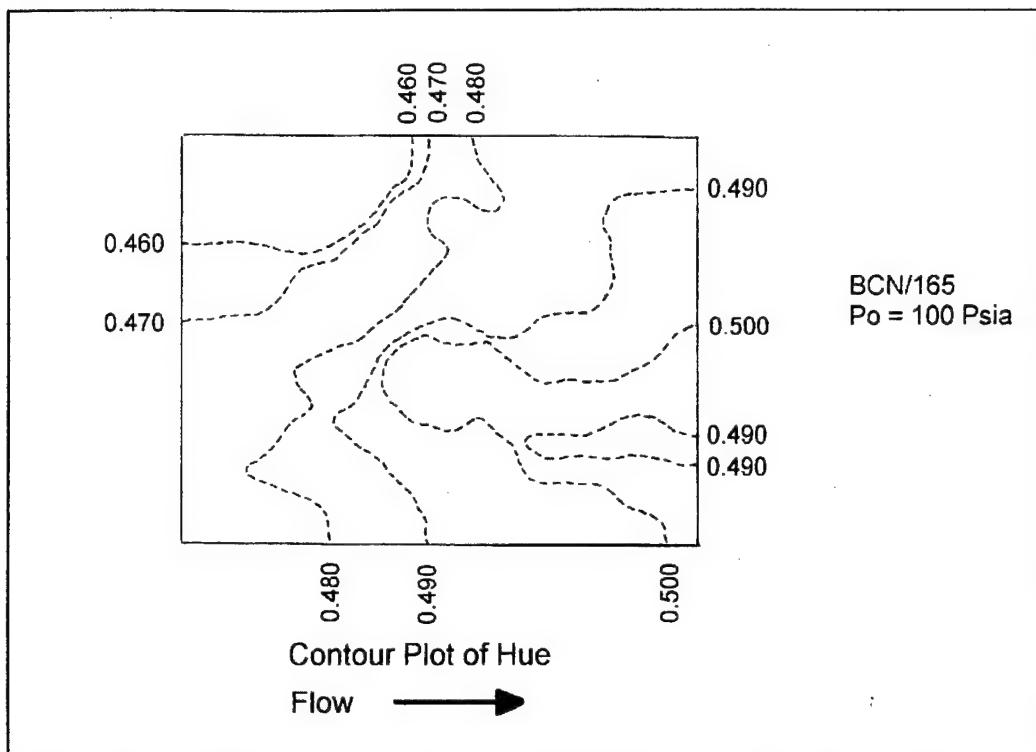


Figure 24. Variation in Hue within a small window on the 'plug' area

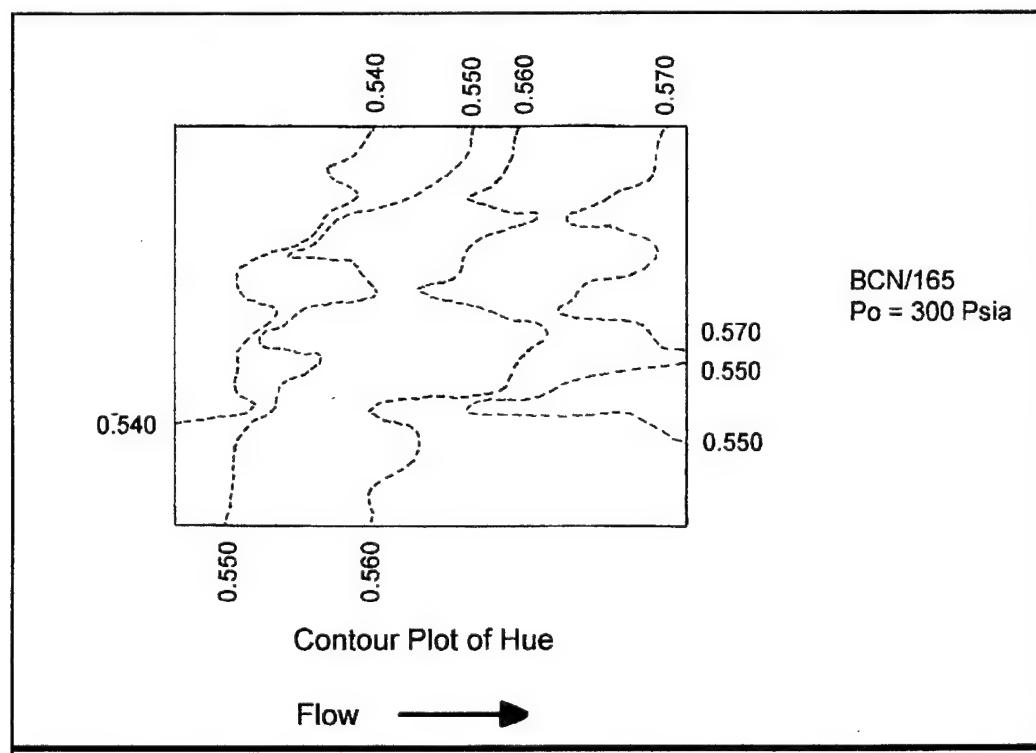


Figure 25. Variation in Hue within a small window on the 'plug' area

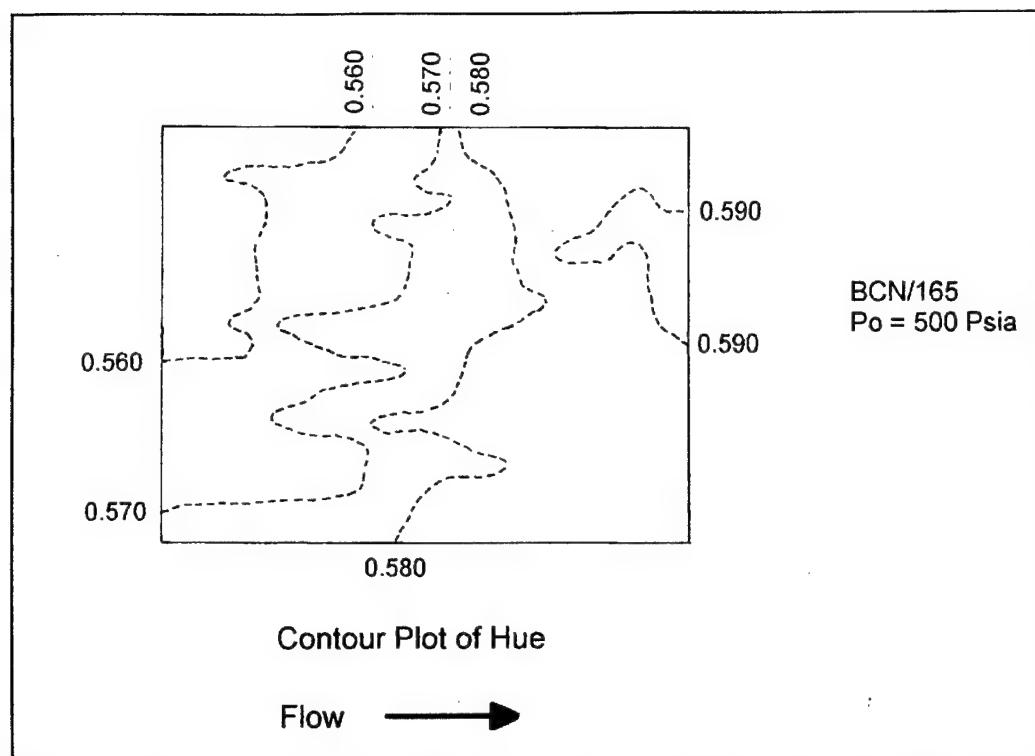


Figure 26. Variation in Hue within a small window on the 'plug' area

In Fiore's work he was able to record the skin friction at 8 stations as measured from the throat for 4 different stagnation pressures, whereas in this work only one station $x = 838$ mm ($x = 33''$) and 3 different stagnation pressures was available. In order to utilize his work only the skin friction data taken from the shear stress gage has been used and this is replotted for clarity in Figure 27. Since his work was carried out at different stations to the one we used and at different stagnation pressures it was necessary to evaluate the skin friction coefficient for our measurement location, and hence the shear stress from interpolating his data.

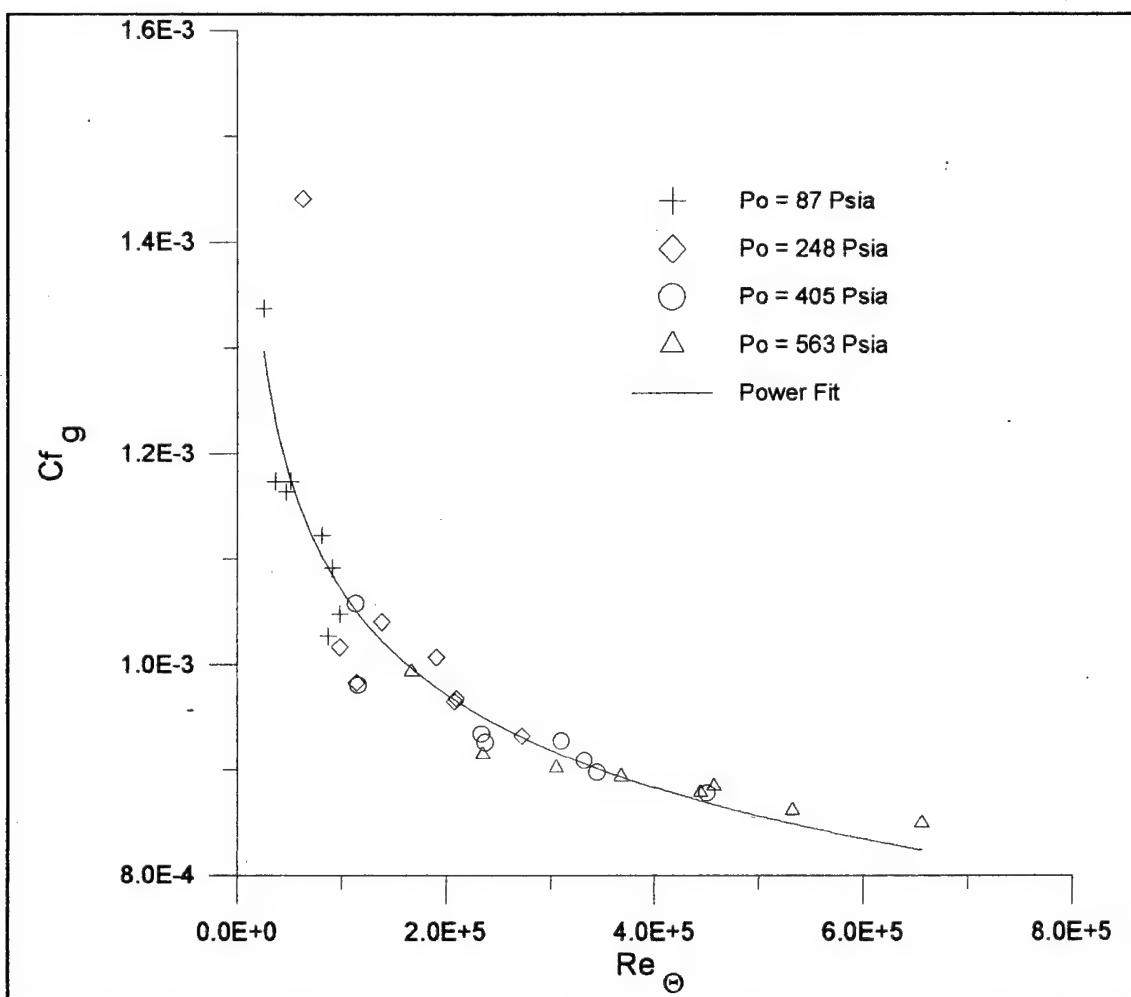


Figure 27. Variation in skin friction coefficient against Reynolds number at different stagnation pressures obtained with the skin friction gage

This was achieved by first plotting Re_θ against P_o for each of the measuring stations, Figure 28, and using this plot and the present values of the stagnation pressures, namely 100, 300 and 500 psia, to evaluate the current values for Re_θ .

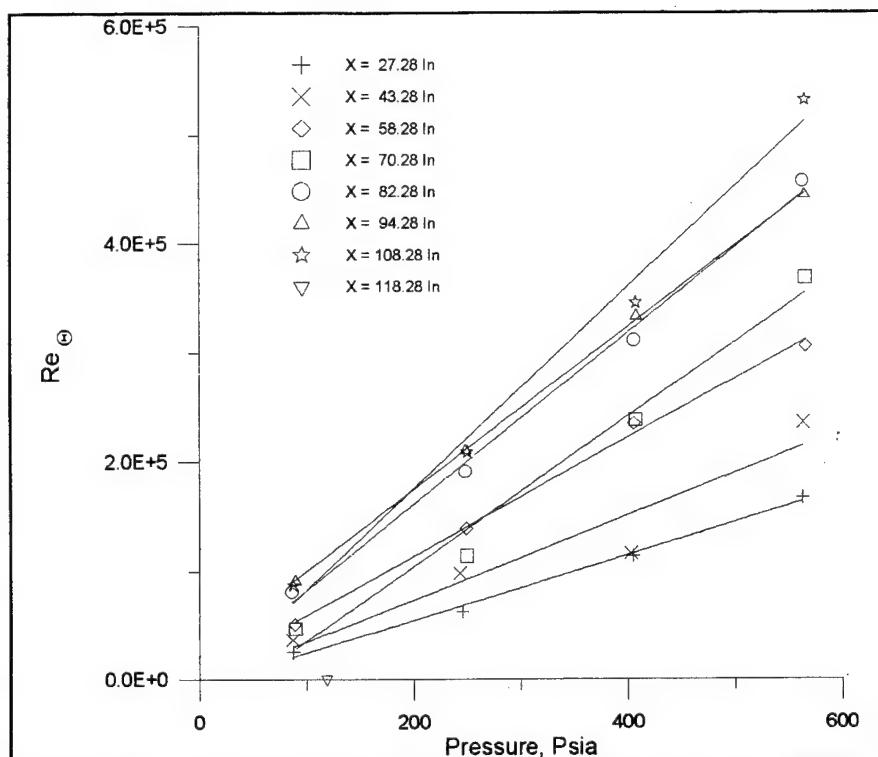


Figure 28. Variation of Reynolds Number with stagnation pressure for different downstream locations from the throat.

Knowing the Reynolds number based on theta, the skin friction coefficient at the present location was determined from Figure 27 and the value of the shear stress ascertained by applying equation (23) from Fiore's report and checked using the velocity profile at the wall as given by equation (43).

Eqn (23)

$$C_f = \frac{\tau_w}{q_e} = \frac{2 (F / A)}{\gamma P_e M_e^2}$$

Eqn (43)

$$\left(\frac{d U}{d y} \right)_w = \frac{\mu_e}{\mu_w} \left(\frac{R_e}{L} \right) U_e \left(\frac{C_f}{2} \right)$$

From these interpolated values the local skin friction coefficient and shear stress values were calculated and are shown in the table below

P_o	Re_e	C_{fg}	$\tau_w \text{ N/m}^2$
100	0.28×10^5	0.00116	142
300	1.04×10^5	0.00107	385
500	1.80×10^5	0.00098	608

The average value of the hue for each of the crystals tested at the 3 stagnation pressures was plotted against the above shear stress and is shown in Figure 29.

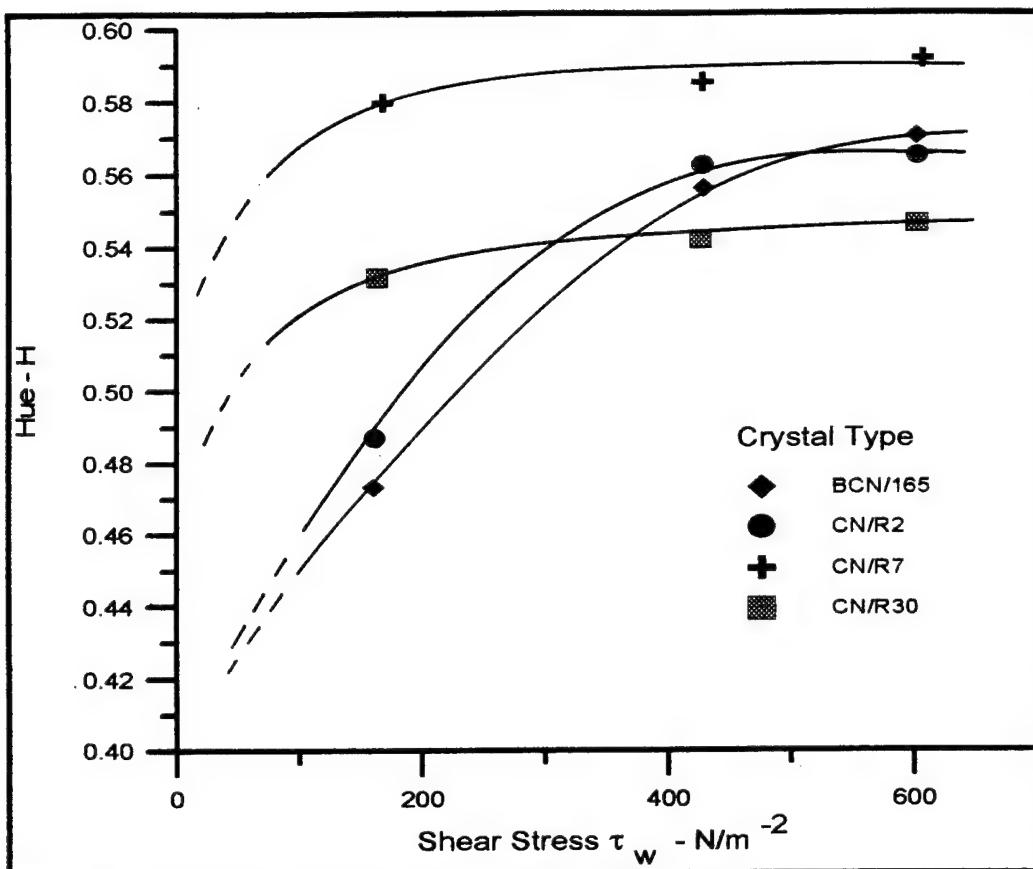


Figure 29. Variation of Hue versus Shear Stress in the Mach 3 Facility for different crystals.

It should also be noted that although there was some movement of the crystals in the downstream direction during the run-time of the experiment all the crystals tested adhered to the tunnel wall and did not 'disappear' from the surface. This is an improvement on the earlier type of crystals that were unable to withstand high shear stress levels found in high speed facilities.

Results of the Mach 2 Tests

In the case of the work carried out in the Mach 2 facility at the University of Cincinnati a number of different experimental approaches were adopted. In one case the crystals were used to provide evidence of the starting shock within the tunnel in order to show that the crystals are capable of responding to changing conditions. In the second case the crystals were applied around half bodies attached to the wall of the tunnel to determine their effect on the local shear stress pattern, with the shear stress values being determined from a calibration of the crystals obtained from a mechanical shear stress rig.

This simple shear stress rig consisted of two optically flat transparent plates. The bottom plate with black card attached to its underside was held fixed while the second, smaller plate was allowed to freely move over its surface. Liquid crystals were placed between the two surfaces and the top plate was moved at a constant speed over the bottom plate using a known force. The subsequent change in the color of the crystals, sandwiched between the two plates, was visualized using the above CCD camera system for analysis of the change in color against known shear stress. Figures 30, 31 and 32 shows how the local shear stress τ_w changes the Hue of the color of the crystal for the different crystals used in this program.

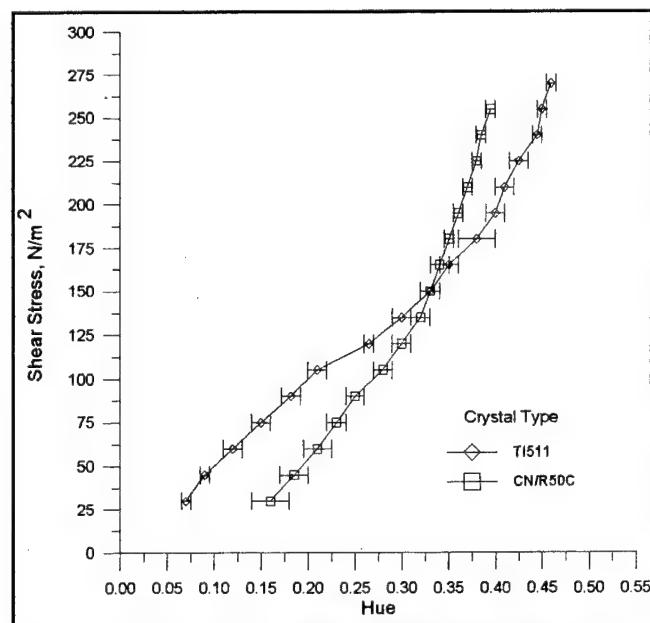


Figure 30. Shear stress calibration for TI511 and CN/R50C

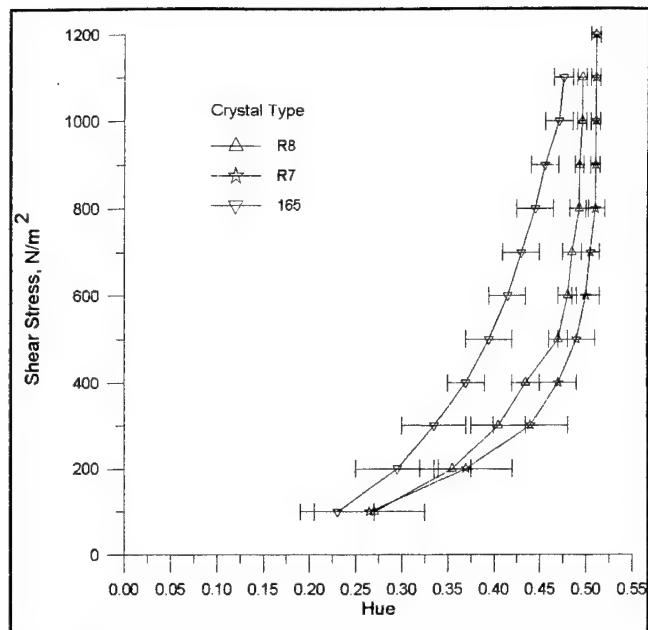


Figure 31. Shear stress calibration for CN/R8, CN/R7 and BCN/165

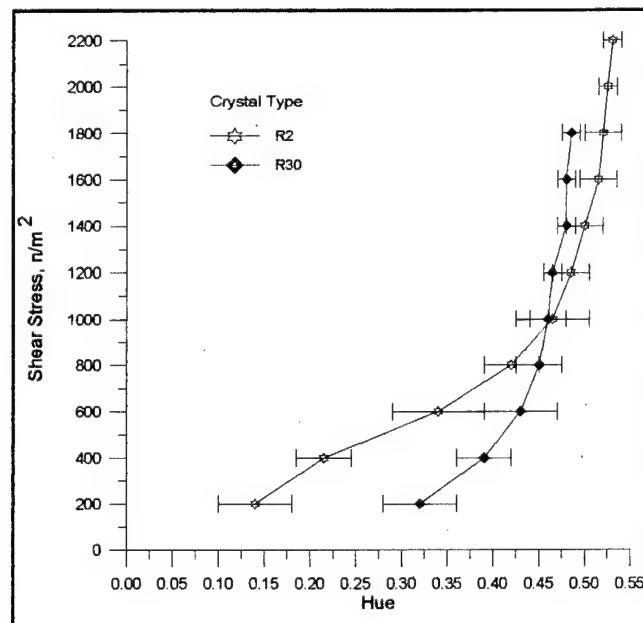


Figure 32. Shear stress calibration for CN/R2 and CN/R30

Tests performed:

Determination of Starting Shock Features

In the case of many high speed facilities the normal experimental run time is often of the order of seconds or minutes before the air for the facility is exhausted. During this time the tunnel parameters have to stabilize before measurements are taken and it is this time period that is very important to the tunnel operating conditions. For supersonic and hypersonic tunnels this time period is related to the passing of the starting shock through the working section and in many applications this has to be inferred from pressure measurements. It is this particular area that the technique of using liquid crystals is to address, and in particular to evaluate the speed of the shock wave as the tunnel is started and before stable conditions occur. The method relies upon coating the surface of the tunnel wall with a thin layer of liquid crystal, of the order of 20 μm , and illuminating this surface with white light while viewing the surface with the color video CCD camera.

In order to assure a constant stagnation pressure in this facility, a primary regulating valve is used to decrease the tank pressure to the required manifold pressure for proper tunnel operation. A second valve of the pneumatic/hydraulic type with feedback is then utilized to regulate the stagnation pressure in the tunnel. The tunnel parameters measured include the manifold, stagnation and static pressures along with heat exchanger air-in and air-out temperatures and the stagnation temperature. For this particular experiment the lower nozzle block in the tunnel was set to produce a freestream Mach number of 2.0.

Liquid crystals of the type CNR2, provided by Hallcrest, were applied in a thin layer, of the order of 20 μm , to the wall of the test section, which was first black anodized. This coating was then illuminated with two 300 Watt Quartz-Halogen light sources while a SVHS color CCD video camera, providing Red, Green, Blue (R G B) output, was positioned normal to the crystals. At present, post processing of the video signal has been achieved by

recording the passing of the shock over the crystals and recording the color change and then employing video digitization to individual frames. The digitized frames were then analyzed using Hue-Saturation-Intensity (H S I).

Figures 33, 34 and 35 shows the starting shock captured by photographing three digitized frames from the SVHS video tape. The shock produces a variation in the local shear stress and this causes the crystals to exhibit different Hue (color) according to the level of the shear, with red being at the lower stress level and blue at the higher. Also shown in this figure is the asymmetry of the shock, and this is due to the asymmetrical wall liner that is positioned upstream of the working section. (However, it should be noted that these Figures have been taken from a video tape and suffers from some degradation and they are shown here for illustrative purposes only, whereas the digitizing process acts upon the frame image).

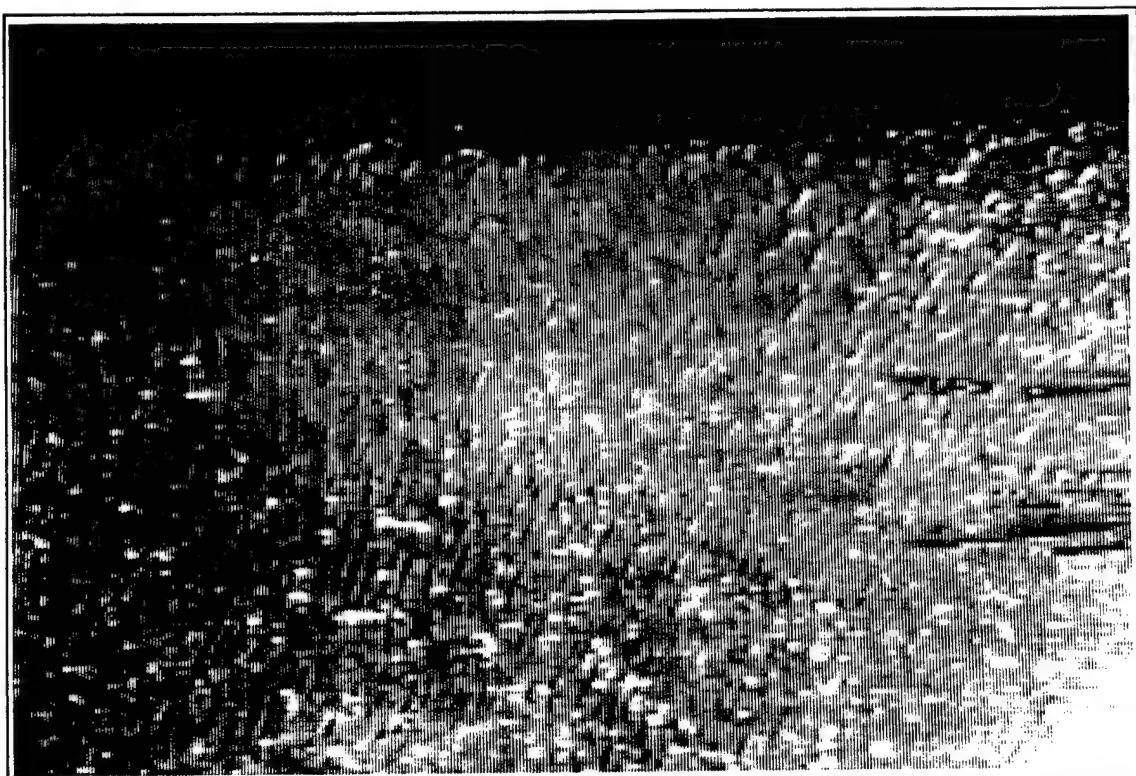


Figure 33. Variation in Hue as a shock passes down the Mach 2 facility at time T

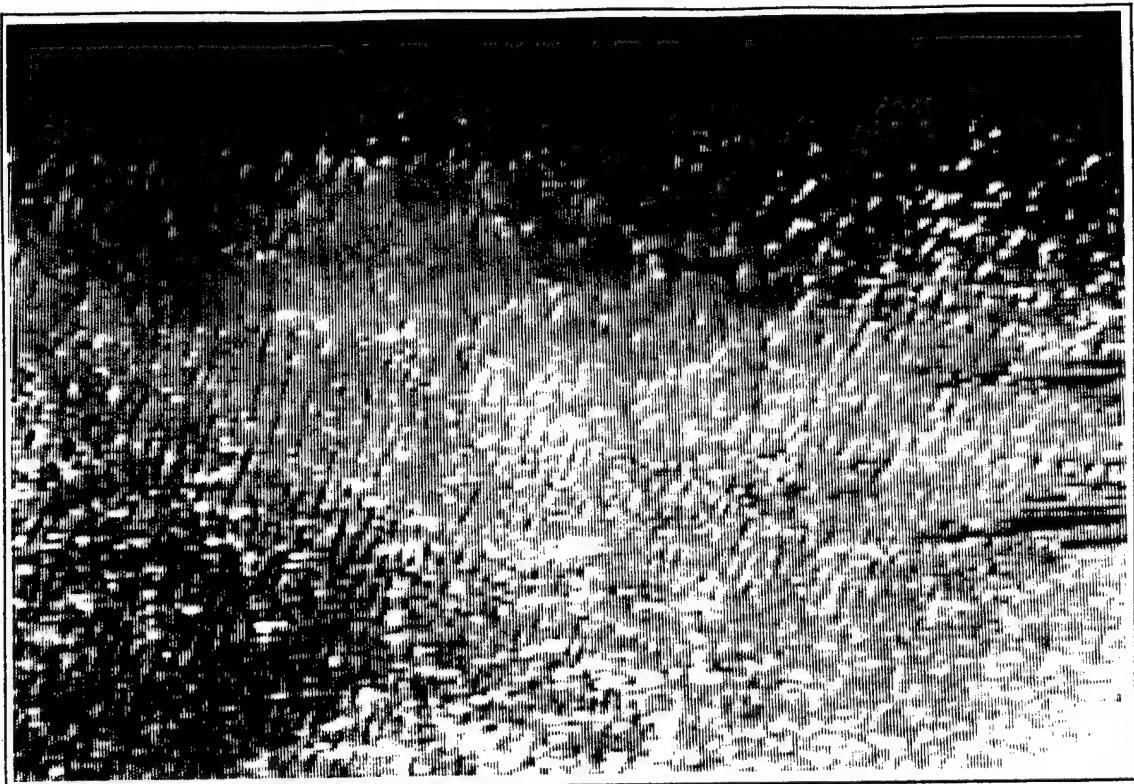


Figure 34. Variation in Hue as a shock passes down the Mach 2 facility at time $T+dt$



Figure 35. Variation in Hue as a shock passes down the Mach 2 facility at time $T+2dt$

The analysis of the frames captured on tape was achieved by setting a sample window and digitizing a number of frames containing evidence of the passing of the shock structure. Since the video frames were captured at a known rate, 30 Hz, the analysis of the movement of this shock position provided the velocity of the shock wave down the tunnel.

Figures 36, 37 and 38 show the contour analysis of the Hue and how it changes as the shock passes through the working section. These three figures were taken as the starting shock traveled through the test section and are shown here, not as consecutive frames, but as every second frame for clarity. In these figures the position of the shock is also drawn and is shown as contours of Hue = 0.09.

The velocity of the shock as it passes down the tunnel was determined from an analysis of the location of this Hue contour and knowing the time between the frames, allowing for the linear scale per pixel. For example, the video digitizing speed was set at 30 frames per second, giving 33 ms between frames. For consecutive frames the average distance between the shock location was approximately 35 pixels with a scale factor of $0.19 +/- 0.02$ mm/pixel, giving a shock velocity of $35 * 0.19 / 0.033$ mm/s, that is $202 +/- 20$ mm/s or approximately $0.20 +/- 0.02$ m/s. Once the shock had passed through this test section the tunnel parameters, as recorded by the stagnation pressure, became constant.

In addition to the shock location and speed, its angle may also be determined from the relative positions of the shock at each stage in its traverse. In this particular case the shock is approximately $35^\circ +/- 3^\circ$ to the freestream flow direction, as measured by the pixel locations of the shock front.

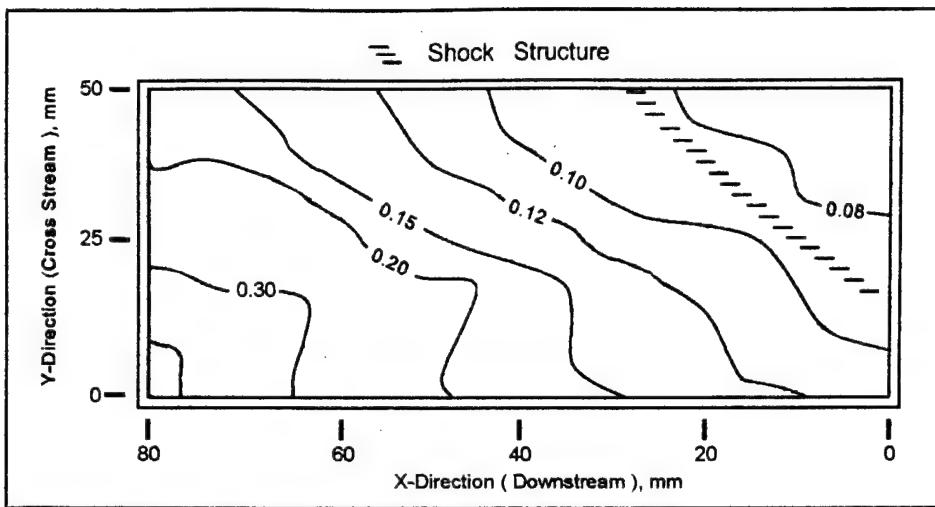


Figure 36. Position of shock front at time T

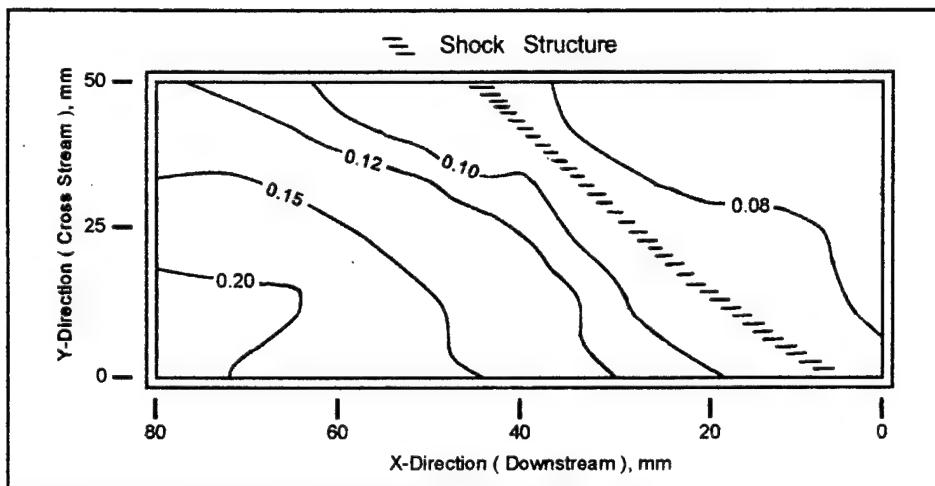


Figure 37. Position of shock front at time $T+dt$

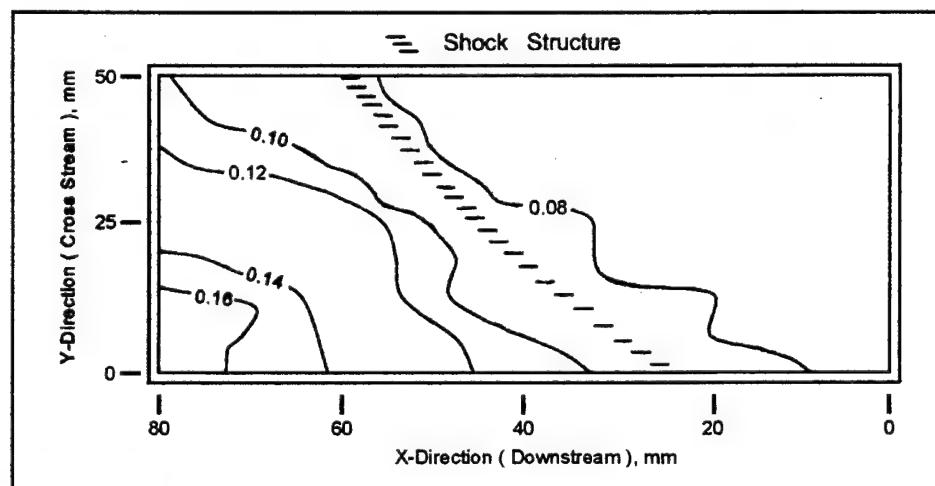


Figure 38. Position of shock front at time $T+2dt$

Determination of shear stress around Half-Bodies at Mach 2

In order to determine the use of these liquid crystals in aerodynamic studies an investigation of the shear stress around three different half-bodies was conducted. The half-bodies, shown in Figure 39, were made from aluminum and their surfaces black anodized.

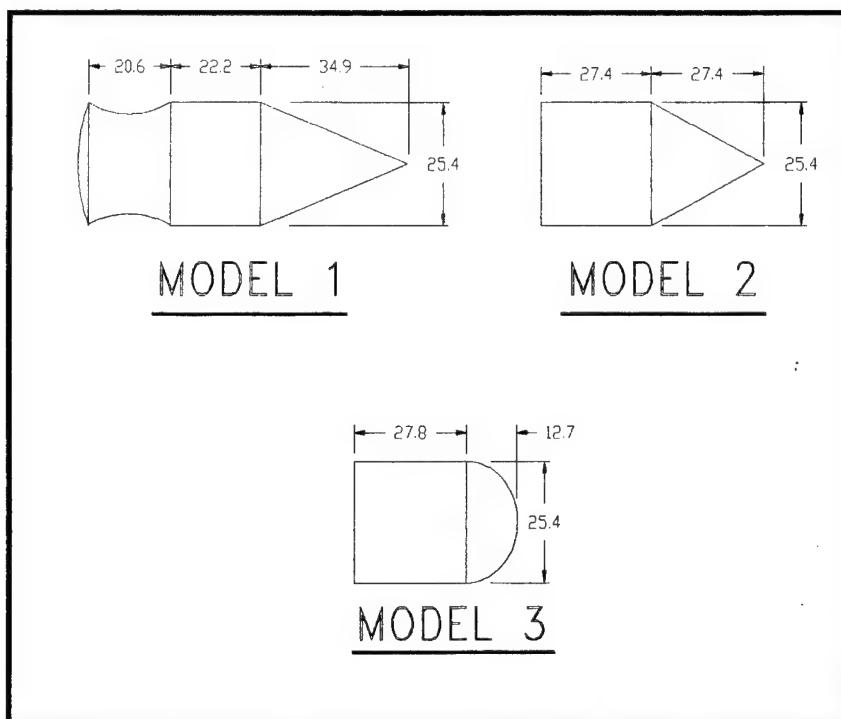


Figure 39. Half bodies for use in the Mach 2 Facility

Different types of crystals, namely CN/R2, CN/R30 and TI511, were applied to the black anodized wall of the tunnel around each of the models in turn. The camera was situated directly in front of the working section so that the complete model could be visualized. The lighting was mounted outside of the tunnel and consisted of two 500W Halogen lamps and one 300W lamp. These were arranged such that:

- a) one 500W lamp was set to the right of the camera at a level position, approximately 75 mm away from the window and angled at 45° towards the test model;
- b) one 500 W lamp was set approximately 300 mm above and to the left of the

camera and 75 mm away from the window and angled at 45° towards the test model; and

- c) the 300 W lamp was set approximately 300 mm below and to the left of the camera and 75 mm away from the window at an angle of 45° towards the test model.

This lighting arrangement was used to prevent a glare from the tunnel window and its surround from saturating the camera response.

Initial investigations using these three crystals at this Mach number revealed some interesting behavior. For example, the response of CN/R30 to the local shear stress around the three bodies was very immediate and saturated very easily, although it did adhere very well to the surface and did not erode. This is not surprising since this crystal is very sensitive to changes in shear stress as shown in Figure 32 (obtained with the mechanical shear stress rig) in which the color changes from the red (hue = 0) to the green (hue = 0.3 -0.4) at low shear rates, even though it has a relatively high viscosity of 7000 cps. The saturation to the blue over a large shear stress range may be due to the breakdown of the ordered crystal structure in this region resulting in a more broadband scattering of the incident light.

The TI511 crystal did not perform at all well. It saturated very quickly and 'disappeared' due to the high shear around the model. This may also be as expected since Figure 30 (again taken from the mechanical shear stress rig) shows that this crystal is sensitive to low rates of shear and coupled with its low viscosity of 250 cps it flowed easily along the tunnel wall.

The crystal CN/R2 with a viscosity of 4500 cps performed well in the shear stress regions around these three bodies. Although it flowed in the direction of the surface flow it adhered to the wall with little loss of the crystal coating and, since its shear stress response, as given by the shear stress rig, is over a fairly large range it provided a good hue distribution around the models. As an example Figure 40 shows a typical flow visualization around

model 2 at Mach 2. However it should be noted that this is a fourth generation picture and there is some degradation in the color component whereas for the analysis the digitization process would have worked upon the first generation taken immediately from the SVHS tape. Figures 40, 41, 42 and 43 shows the hue distribution and local skin friction coefficient distribution around models 2 and 3, with the skin friction coefficient being calculated from the above calibration curves. It should also be noted that only the region immediately upstream of the body and the body surface was coated with crystals.

In the case of model 2 the skin friction coefficient C_f is normalized by the reference skin friction coefficient C_{f0} measured at the most upstream location in the image on the wall along the line of symmetry of the model, Figure 42. The rapid increase in the shear stress on the wall along the nose of the model, from its tip to the main body, is highlighted as are the shear stress levels associated with the wake shear layers.

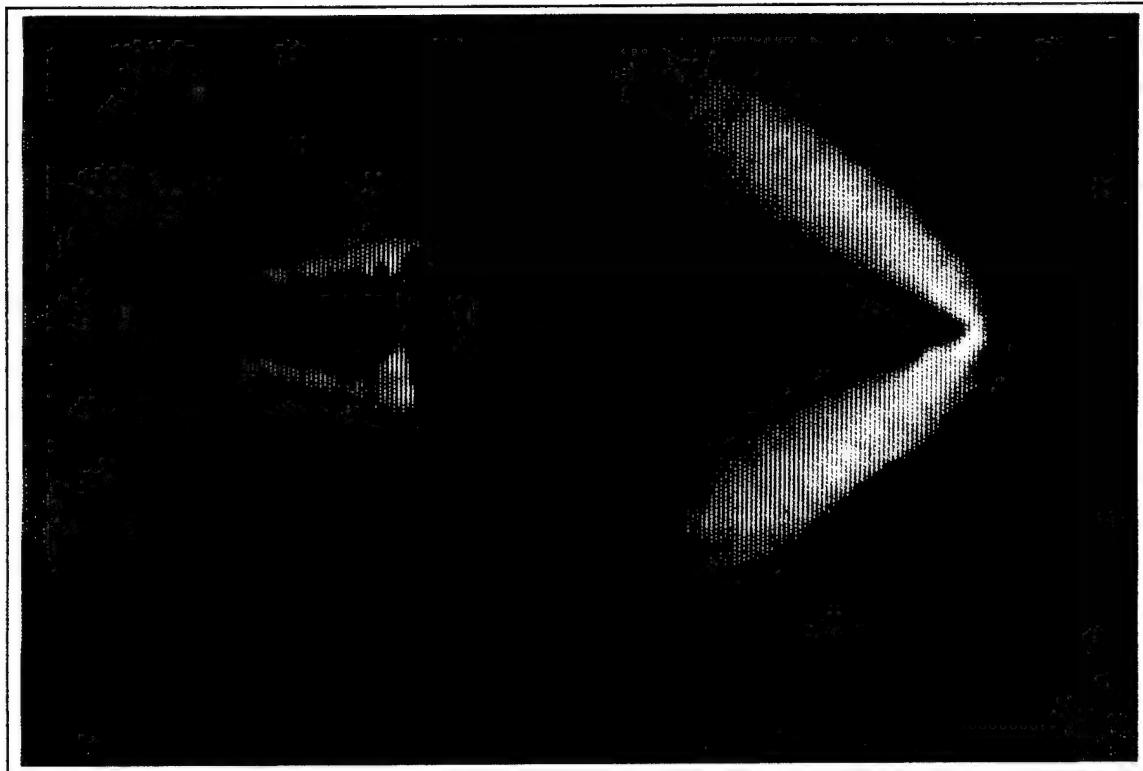


Figure 40. Variation of Hue around half model #2 at Mach 2

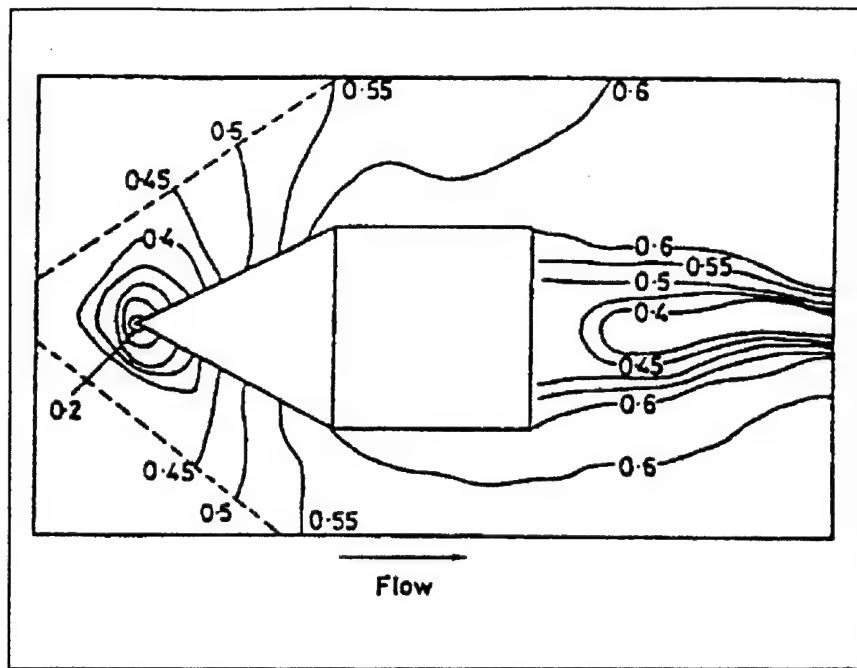


Figure 41. Hue distribution around model 2

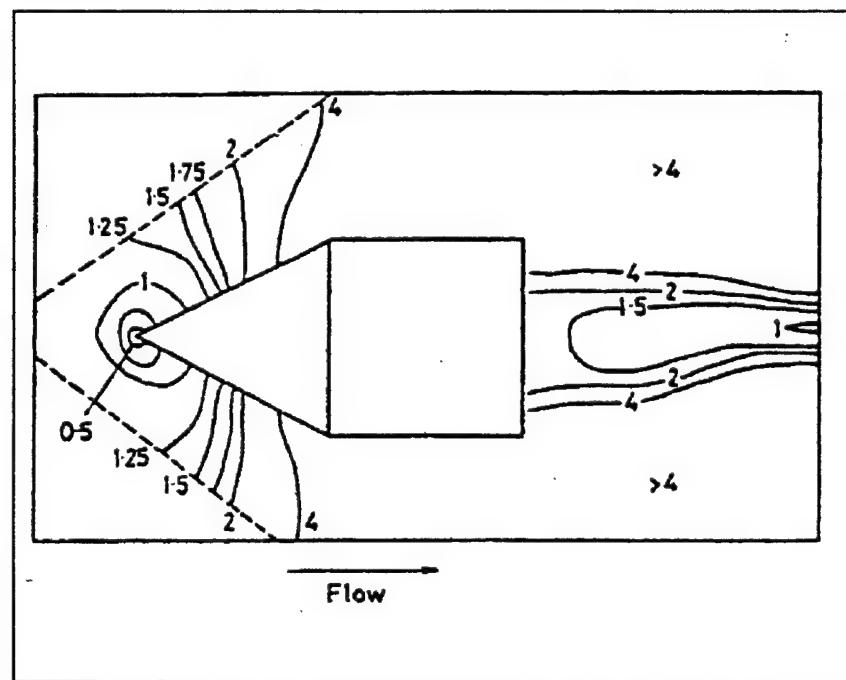


Figure 42. Normalized skin friction coefficient around model 2

The hue distribution around model 3, set at an angle of 16.5° to the flow, is shown in Figure 43. As before, the local shear stress distribution has been normalized by using the

most upstream center-line skin friction value taken from the image and is shown in Figure 44. It is worth noting that the highest shear levels occur to the side and in the immediate wake of the model.

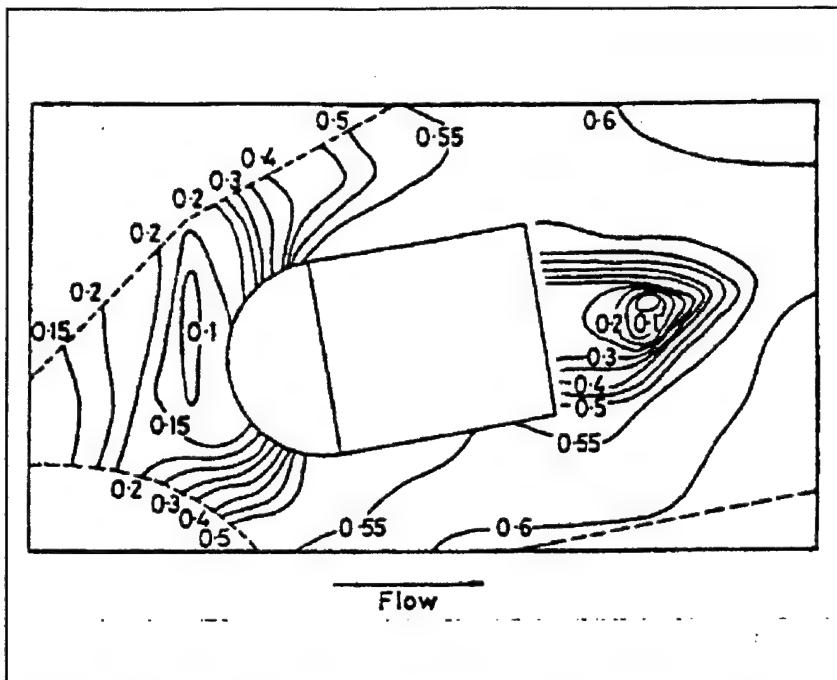


Figure 43. Hue distribution around model 3 set at 16.5

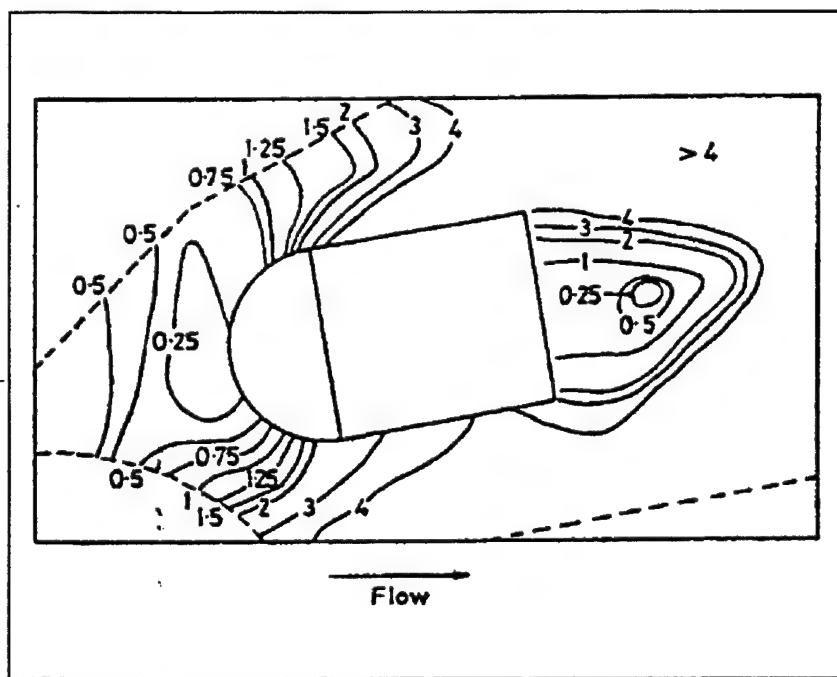


Figure 44. Normalized skin friction coefficient around model 3

Although these wind tunnel tests may only be regarded as approximate since the shear stresses in some regions of the distributions are greater than the maximum produced in the mechanical calibration rig, they do provide evidence of the potential of using liquid crystals for shear stress measurements at high speed.

In addition to the previous analysis of the half models Figures 45 and 46 show qualitatively the change in the hue of BCN/165 of Model 1 set at an incidence of 2° . Figure 45 was taken during start-up of the tunnel and highlights the asymmetry of the flow in the base region, whereas Figure 46 was taken at steady conditions at Mach 2 and shows distinctly the asymmetry of the shear stress around the body of the model.



Figure 44. Change in Hue around model #1 on start-up

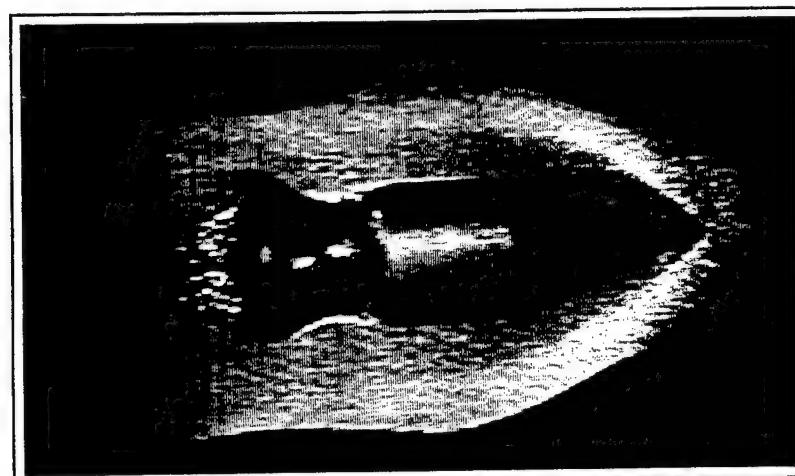


Figure 45. Change in Hue around model #1 at Mach 2.

Conclusions

This present research program set out to determine two factors and they were:

- I) were shear stress sensitive liquid crystals capable of adhering to the wall of a high speed facility without 'disappearing' rapidly, especially at Mach 3, and
- ii) could they be calibrated aerodynamically?

Although the contract was not increased in financial terms the investigators enlarged the scale of the test program to encompass two facilities in order to provide further evidence of the suitability of using liquid crystal for aerodynamic studies.

In the Mach 3 Facility

In the case of this facility skin friction results at one location in the roof of the tunnel was known and from these results the shear stress values were computed. However it should be noted that over the three stagnation pressures that were run, namely 100, 300 and 500 psia, the local skin friction C_f only changed by approximately 0.00018 from 0.00098 to 0.00116, an extremely small increment over which to do an accurate calibration. Nevertheless, the crystals that were tested all were capable of adhering to the wall of the tunnel although two of them, namely CN/R7 and CN/R30 were outside the range of their response. The other two crystals, CN/R2 and CNR/165 both showed evidence of calibration over this range of skin friction.

In addition, the percentage change in the skin friction over the pressure range tested was some 15.5% while the percentage change in the value of Hue for crystal CNR/165 was approximately 17%, and was of a similar value for crystal CN/R2.

In the Mach 2 Facility

In this facility two different experimental projects were performed. The first concerned the effect of the starting shock down the tunnel before it reached steady state conditions, and the second was concerned with determining the shear stress distribution around half-bodies utilizing a calibration based on a mechanical shear stress rig.

Case 1- Starting Shock down the Mach 2 tunnel

A simple effective way for determining the starting transients in an intermittent supersonic wind tunnel has been shown. Liquid crystals of the Cholesteric type were used to observe the passing of the starting shock through the test section of a supersonic tunnel and included determination of its propagation velocity such that stabilization of the tunnel parameters may be inferred. This method of using liquid crystals may be applied and used both from a qualitative and quantitative viewpoint.

Case 2 - Shear Stress determination around Half Bodies

Full field surface shear stress measurements using stress sensitive liquid crystals around half bodies has been demonstrated at Mach 2. However, since it is known that the lighting and viewing angles are important in the determination of the color component for a given shear stress direction the magnitude of the derived shear stresses in Figures 42 and 44 may not be as accurate as that obtained by current methods. This variation is the result of an experimental setup utilizing several lighting angles as opposed to a single well defined angle and known stress orientation. Therefore, further work is needed to examine in more detail the manner in which the shear stress direction and its magnitude changes the perceived color reflected by the crystals. Bearing the above points in mind liquid crystals can be used for qualitative flow analysis and, coupled with a video digitization system, they may be used in a quantitative manner.

General comment

Although the program of assessing these crystals has clearly shown that they may be used successfully at high Mach number a number of questions still remain to be answered. In particular the lighting, viewing and method of applying the crystals to the surface is paramount, as well as the effect of surface curvature. This latter effect may be addressed once further information concerning lighting angles has been solved. Furthermore, it is evident from this work that the value of the viscosity is not a valid method of deciding for what range of speed a particular crystal is suitable. In addition, the calibration obtained in the mechanical rig is not reflected in the aerodynamic calibration and this may be due, in part, to some compressibility effect that has not been recognized to date.

However, for the purposes of this contract, it has been shown that shear stress sensitive liquid crystals may be used in high speed facilities and may be calibrated aerodynamically.

Recommendations

A number of comments may be made with respect to improving our knowledge of the application of liquid crystals to measuring surface shear stress in high speed flows. In order to specify these more succinctly it is perhaps more instructive to provide an overview of what knowledge we have at the present time and what is required to be understood before further advances may be made and the technique can be used successfully as a measurements tool.

what do we know?

- the crystals will adhere to the wall at high speed
- depending on the crystal they can be calibrated aerodynamically at Mach 3
- they will reflect changes in color as the shear stress is increased

what don't we know?

- what is the best lighting and viewing direction?
- how thick should a crystal layer be?
- the viscosity of the crystal mixture gives no indication of relative performance, particularly the color reflected at a given shear stress
- is there a compressibility effect?
- how to improve a crystal for a specific shear stress bandwidth
- the true mechanism by which these crystals reflect their color

what is the Priority area?

- what is the best lighting and viewing direction?
- how thick should a crystal layer be?
- which crystal to use for a given shear stress field
- must determine the method of applying the crystals to the surface
- calibrate over a larger shear stress range than has been performed
- must determine if there is a compressibility affect

what is needed at a later date?

- develop the system as a real-time full field shear stress analysis package
- determination of the crystal color over the surface of a non-flat body

This project has provided a strong platform upon which further work on the use and the application of liquid crystals for high speed aerodynamics may be performed. The knowledge gained from a series of tests has shown the merit for using these crystals and it is recommended that a further study is initiated to quantify their performance in high speed flows especially those in which compressibility effects are dominant.

Nomenclature

R	Red component of color
G	Green component of color
B	Blue component of color
H	Hue of the color
S	Saturation of the color
I	Intensity of the color
U_e	Velocity at edge of boundary layer
C_f	Skin Friction
$\frac{dU}{dy}$	Velocity gradient at the wall
P_o	Stagnation pressure
μ_e	Viscosity at edge of boundary layer
μ_w	Viscosity at the wall
R_e	Reynolds number
M_e	Mach number at the edge of boundary layer
L	Distance from the throat
q_e	Dynamic pressure at the edge of boundary layer
τ_w	Shear stress at the wall

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the work to be undertaken in the Mach 3 facility. Thanks must also go to Mr R DiMicco, Mr C Fox and Mr P Kunkel for their assistance in running the Mach 2 facility. Furthermore, the authors would like to thank Hallcrest for their guidance and assistance in providing Liquid Crystals capable of withstanding the wall shear stress in these wind tunnel facilities.

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Appendices

Publications associated with this project

Paper 1

Determination of starting shock velocity in a supersonic wind tunnel

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and

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Submitted and accepted for publication as a Technical Note in AIAA Journal, 1995.

Paper 2

The evaluation of shear sensitive liquid crystals at Mach 3

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and

Norman Toy and Eric Savory

University of Surrey, Guildford, United Kingdom GU2 5XH

16th International Congress on Instrumentation in Aerospace Simulation Facilities, Wright-Patterson AFB, Dayton, Ohio. 1995

Paper 3

Assessment of shear stress sensitive liquid crystals for high-speed aerodynamics

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and

Norman Toy and Eric Savory

University of Surrey, Guildford, United Kingdom GU2 5XH

ASME/JSME Fluids Engineering Annual Conference & ASME/EALA 6th International Conference on Laser Anemometry; Hilton Head, SC, August 1995.